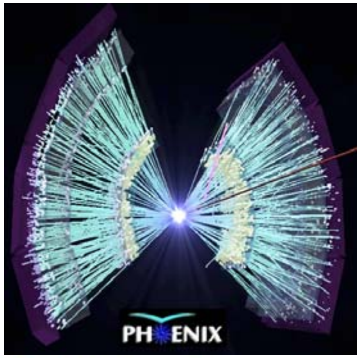
40th Anniversary of Quantum ChromoDynamics (QCD) Experimental Viewpoint: High p_T physics from ICHEP 1972 to ICHEP 1982

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA



Physics Colloquium
BNL
April 9, 2013

Introduction

I was stimulated to give this talk by George Zweig's colloquium. Photo is of George and Stan Brodsky taken at a conference on the 40th anniversary of QCD , last August, organized by Harald Fritzsch. Zweig and Gell-Mann developed the quark-structure model of elementary particles in ~1964. Gell-Mann thought that it was just a mathematical symmetry. Zweig???

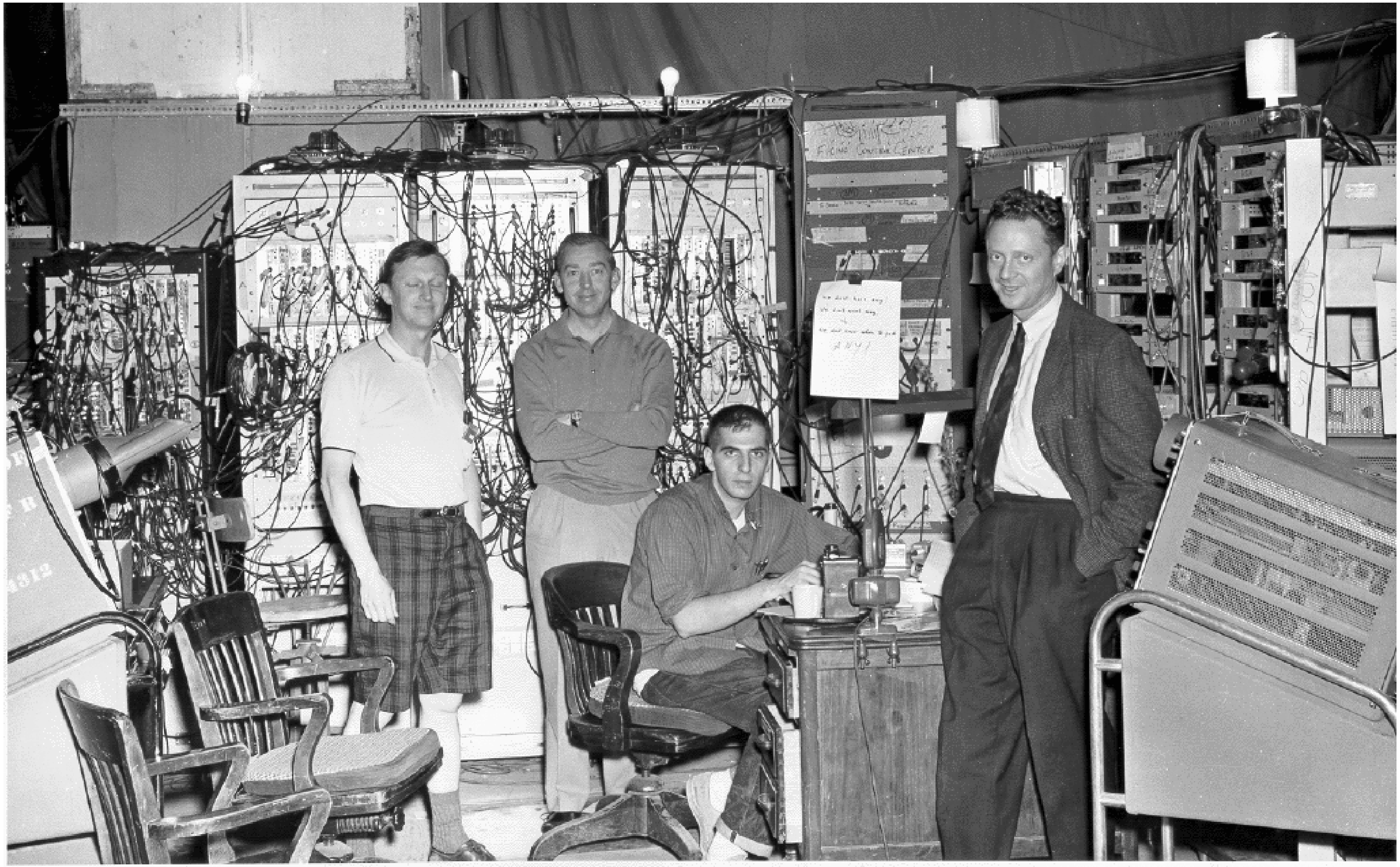
e.g $\boxed{\Omega^- = (sss)}$

Nobody seemed to ask what held the quarks together.

Harald Fritzsch and Peter Minkowski c.2011

Fritzsch and Gell-Mann first proposed QCD at the 1972 ICHEP at Fermilab/Chicago, which I attended. It made no impression on me. (See what made an impression a few slides later.) However my favorite QCD reaction is direct-γ production Fritzsch and Minkowski, PLB **69** (1977) 316-320, a classic paper!

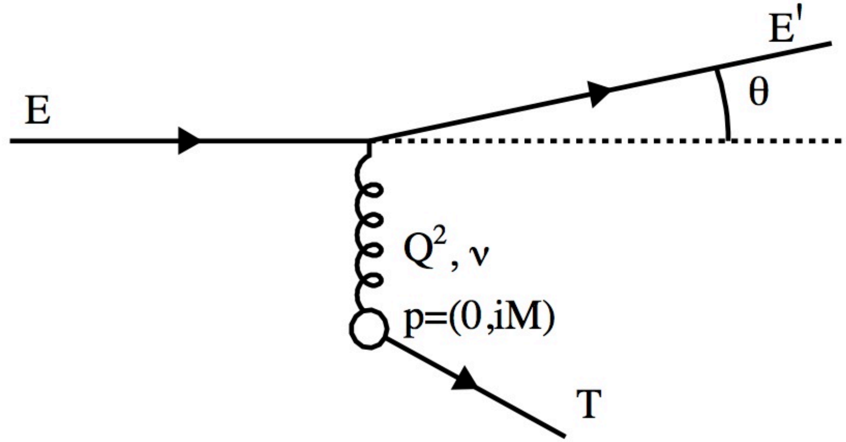
My Mentors-AGS floor c. 1963



Tinlot, Cool (ALD), MJT, Lederman

My thesis experiment, muon-proton elastic scattering---``Why does the muon weigh heavy?" We still don't know! Next beam to left: first neutrino expt (Nobel Prize); over in inner Mongolia CP violation (Nobel Prize). Those were the days!

But I learned the kinematics of elastic scattering



A particle of energy E, charge *e*, scatters elastically (2 to 2 in modern terminology) from a particle of mass M, charge *e* at rest (electro-magnetic scattering). The particle initially at rest recoils with kinetic energy, $T=E-E'=\nu=Q^2/2M$ where Q^2 is the four-momentum transfer square, $Q^2=4EE'\sin^2\theta/2$, E′ is the energy of scattered particle.

$$\boxed{\nu = Q^2/2M}$$

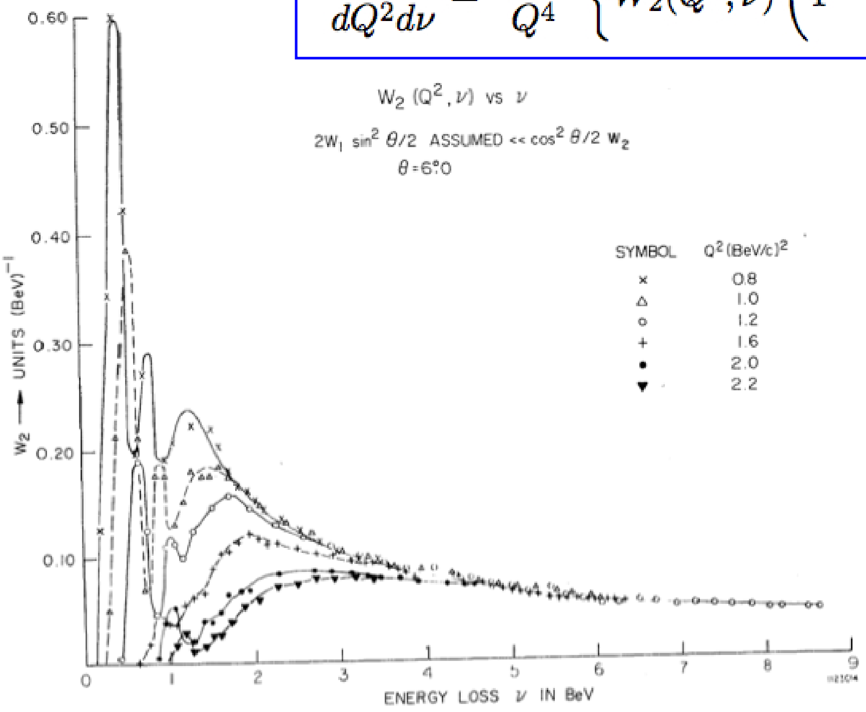
End of Introduction and on to 1972, But first

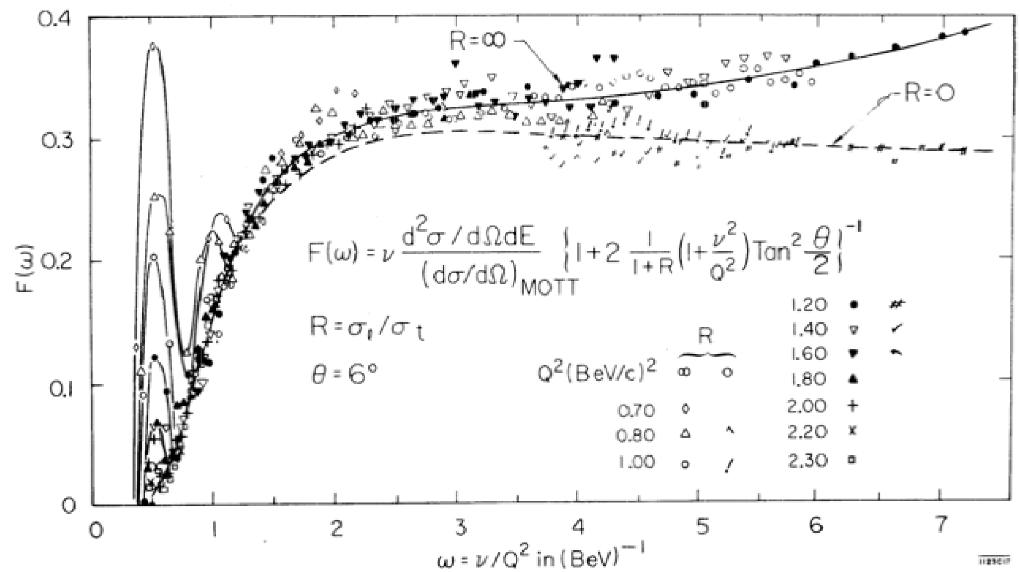
It all began at the 1968 ICHEP in Vienna. Panofsky reported on the first DIS results from SLAC which Bjorken had clarified using scaling arguments

From Panofsky ICHEP 1968-SLAC e-p Deeply Inelastic Scattering

$$\frac{d^2\sigma}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^4}\left\{W_2(Q^2,\nu)\left(1-\frac{\nu}{E}-\frac{Q^2}{4E^2}\right)+2W_1(Q^2,\nu)\frac{Q^2}{4E^2}\right\}$$

$\nu > Q^2/2M$





The old way, hard to understand $W_2(Q^2,\nu)$ vs energy loss ν

The new way, Bjorken Scaling $F_2=\nu W_2(Q^2,\nu)$ scales vs $\omega=\nu/Q^2$ i.e. collapses onto one curve

Bjorken Scaling in Deeply Inelastic Scattering and the Parton Model---1968

- The discovery that the DIS structure function

$$F_2(Q^2,\nu) = F_2(\frac{Q^2}{\nu}) \qquad (1)$$

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \qquad (2)$$

independently of Q^2 $(\sim 1/r^2)$

- as originally suggested by **Bjorken** Phys. Rev. **179**, 1547 (1969)
- Led to the concept of a proton composed of point-like **partons**. Phys. Rev. **185**, 1975 (1969)
  - The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$

$$\nu = \frac{Q^2}{2Mx}$$

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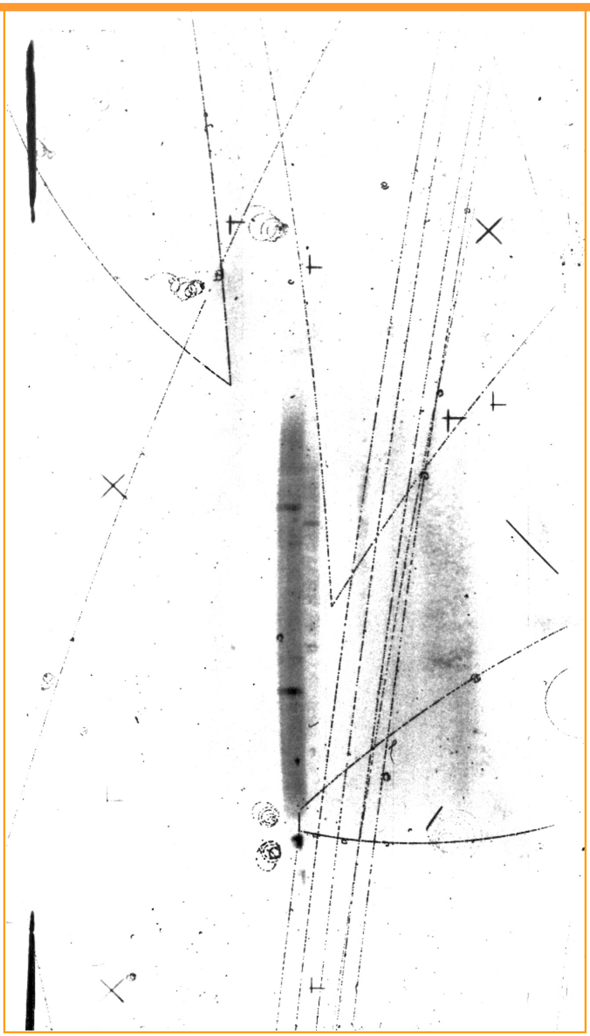
(DIS=elastic scattering from a parton of mass *Mx*) $\nu = \frac{Q^2}{2Mx}$

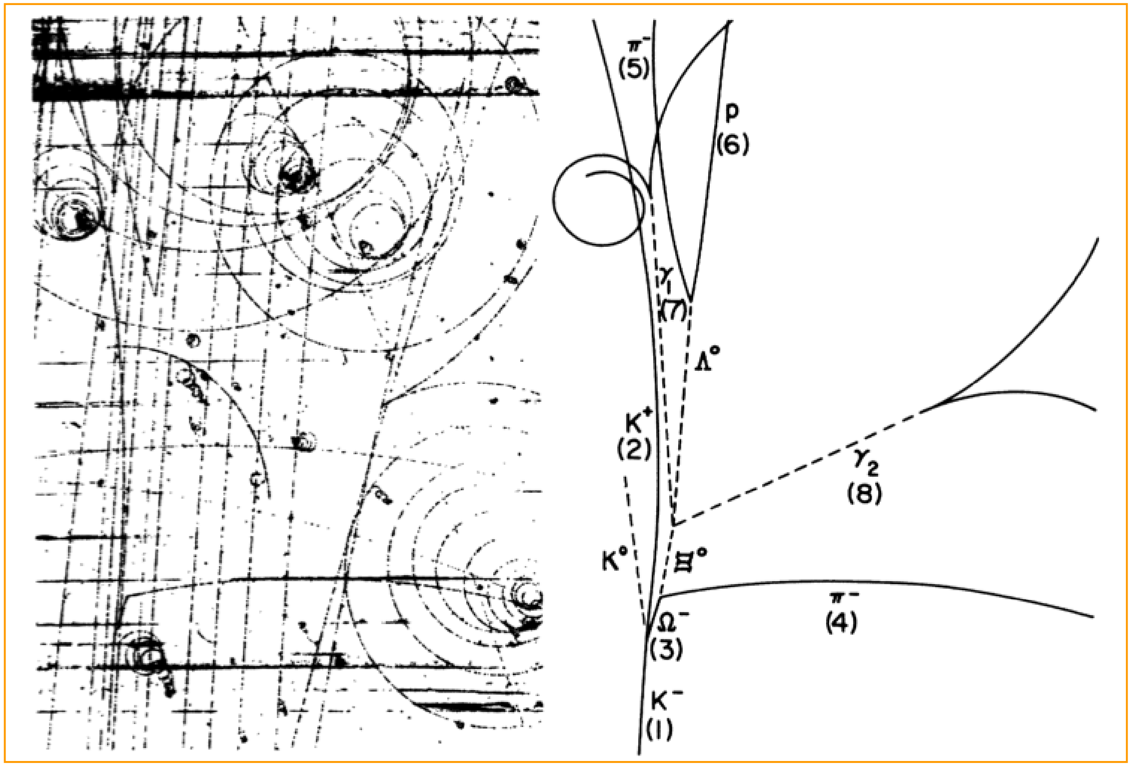
- The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$

The 1960's--Typical High Energy Physics



$K^- + p \longrightarrow \Xi^- + K^o + \pi^+$

$\hookrightarrow \Lambda^o + \pi^-$



Ω^- (sss)

BNL-Barnes, Samios *et al*., PRL**12**, 204 (1964)

Why were some people studying "high p_T" physics in the 1960's?

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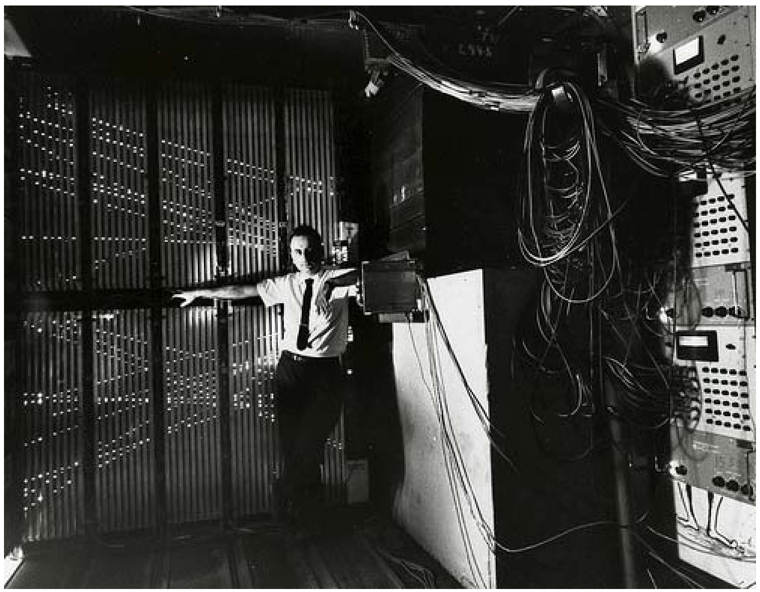
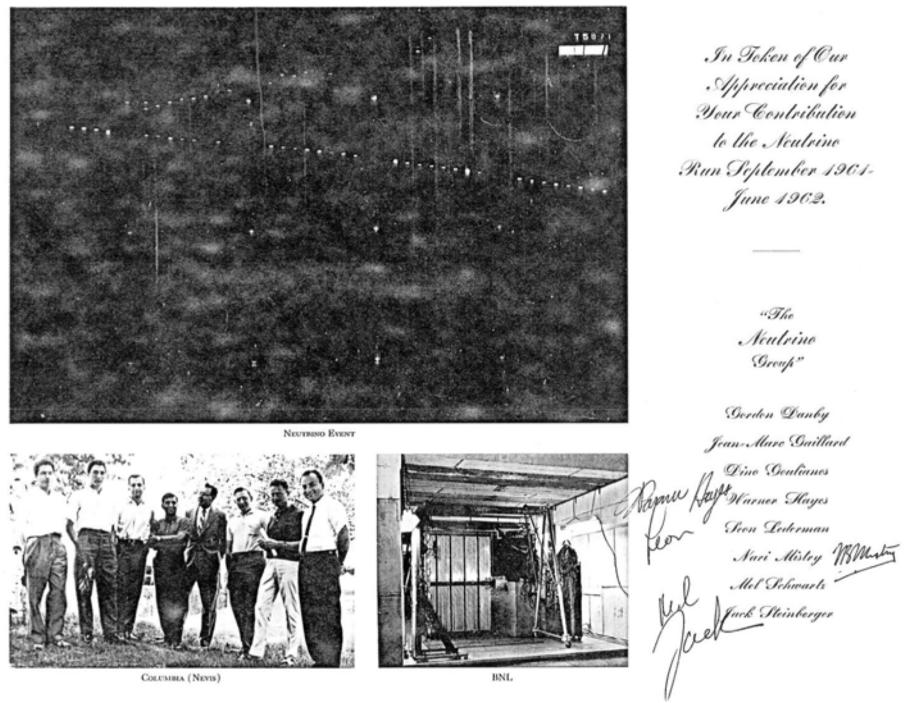
They were searching for the W boson.

Why were some people studying "high p_T" physics in the 1960's?

• The first opportunity to study weak interactions at high energy was provided by the development of neutrino beams at the new accelerators in the early 1960's CERN-SpS , BNL-AGS.





• However, it was soon recognized that the intermediate (weak) boson $W^{\pm}$, might be more favorably produced in nucleon-nucleon collisions.

The 'Zichichi signature' for the W boson

Proc. 12th ICHEP, Dubna 1964

MUON-PROTON ELASTIC SCATTERING AT HIGH MOMENTUM TRANSFERS *

R. Cool, A. Maschke
Brookhaven National Laboratory, USA
L. Lederman, M. Tannenbaum
Columbia University, USA
R. Ellsworth, A. Melissinos, J. Tinlot, T. Yamanouchi
University of Rochester, USA
(Presented by J. TINLOT)

We have studied the elastic scattering of negative muons from liquid hydrogen at momentum transfers of 550 MeV/c to 1050 MeV/c ($q^2 = 7$ to 26 fermi^{-2}), using a detecting array of spark chambers and scintillation counters. The experiment was performed at the AGS accelerator of the Brookhaven National Laboratory, and the runs were divided into three stages, as shown below:

of the proton in an aluminum plate spark chamber. One also measures the directions of the recoil proton and the recoil muon. This is equivalent to measuring three independent angles, from which one can infer for each event the value of k, and still overdetermine the scattering event by two degrees of freedom. This redundancy is used to select true scattering events from the background of false events, such as random coincidences, inelastic $\mu - p$

It appears that, within the uncertainties of these preliminary results, the muon scattering cross section for momentum transfers of up to 1 Gev/c is correctly described by the Rosenbluth formula and the $e-p$ form factors. It is still too early to attempt a more quantitative definition of the possible deviation from the electron predictions.

ДИСКУССИЯ **DISCUSSION**

A. Zichichi.

I would like to ask Dr. Tinlot what is the accuracy of the measured cross section at 1 GeV/c momentum transfer.

J. Tinlot.

The accuracy of the highest point (statistical error only), at 1.05 GeV/c, is 25%; at 950 MeV/c, the error in the point is about 15%.

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ДИСКУССИЯ DISCUSSION

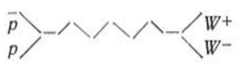
A. Zichichi

In connection with the problem of observing the production of intermediate bosons, I would like to mention that we have been studying at CERN two schemes:

1) $\bar{p}+p \to W^+ + W^-$

$$\left.\begin{array}{l} W^- \to e^- + \nu_e \\ W^+ \to \mu^+ + \nu_\mu \end{array}\right\} \to \mu^\pm,\ e^\mp .$$

This process is described by the following Feynman diagram



Notice that this process is proportional to α^2 where α is the electromagnetic coupling constant.

2) The second proposal studied would use the internal target of the proton synchrotron with 10^{12} protons per pulse incident onto the target. The process would be $p + \binom{p}{n} \to W^\pm +$ anything. We would observe the μ's from W-decays. By measuring the angular and momentum distribution at large angles of K and π's, we can predict the corresponding μ-spectrum. We then see if the μ's found at large angles agree with or exceed the expected number. A supplementary check can be made by measuring the polarization of these μ's. The polarization indicates the origin of these μ's. Notice that the cross section for this process goes with $\sqrt{g}$, where g is the β-decay coupling constant.

B. Pontecorvo

I would like to use the fact that you are all tired in order to make a remark of linguistic rather than sicentific character. All the speakers used as notations for neutral leptons the letters ν_e and ν_μ. This seems to be a very convenient notation. On the other hand, the terms which are usually used for neutral leptons-electron and muon neutrinos (and even «electron and muon type of neutrino!»), are too cumbersome. True, sometimes for ν_e the word «neutrino» is used and for ν_μ, the word «neutretto». The last term, however, is not very satisfactory since the last thirty years lost of particle including strong interacting particles had been called that way. In addition, it seems to me that both types of neutral leptons should conserve in their «name» the root «neutrino», which is widely associated with the unique

3* 35

The ‘Zichichi signature’ for the W boson

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UA1,UA2, CERN 1983
W boson discovery

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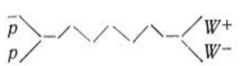

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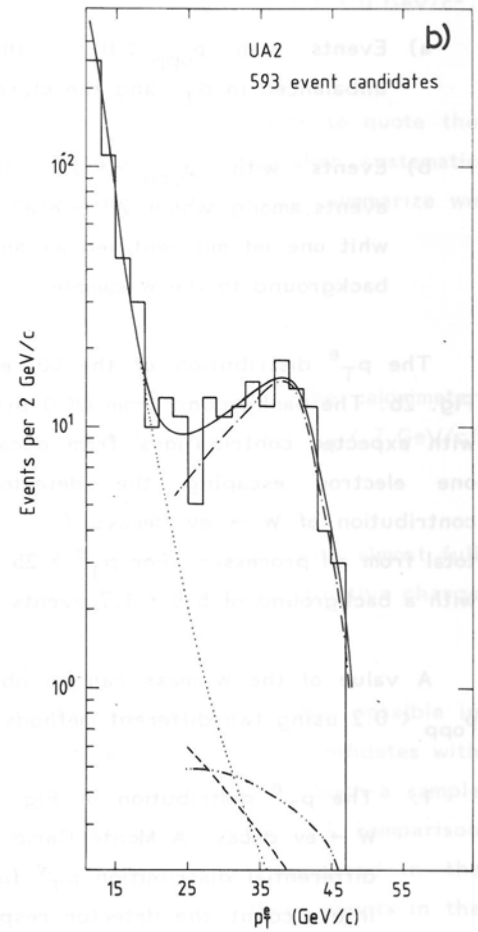
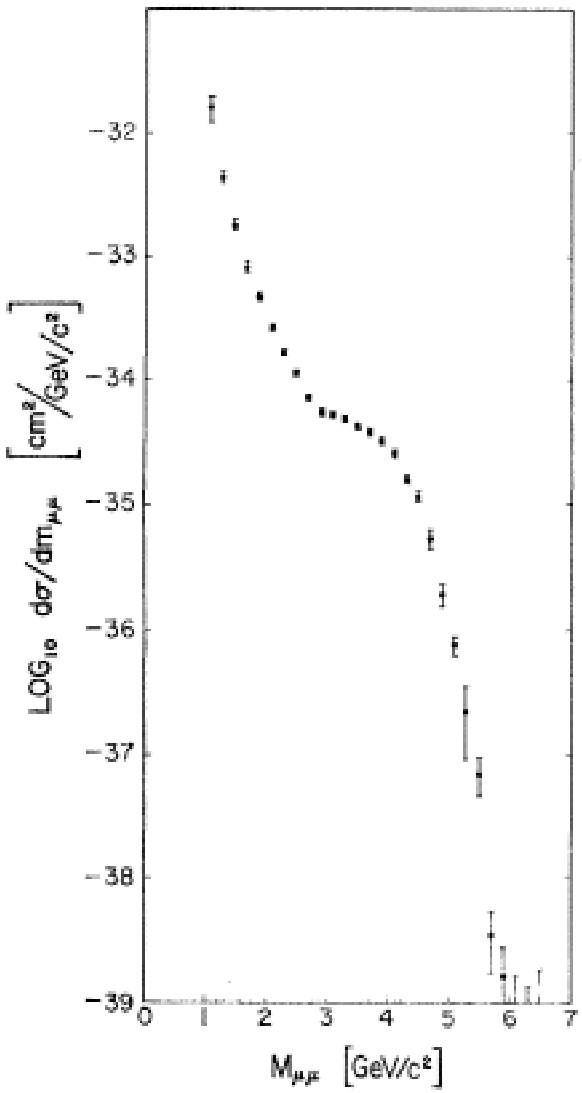


Searches for W boson in p-p collisions

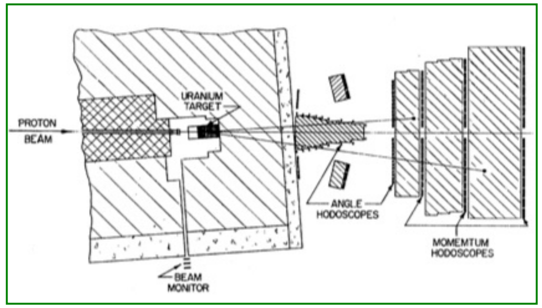
- 1965-1969 Beam dump experiments at ANL-ZGS and BNL-AGS looking for "large angle" muons didn't find any. [ZGS-Lamb, et al PRL **15**, 800 (1965), AGS-Burns, et al, ibid 830, AGS-Wanderer et al, PRL **23**,729(1969)]
- How do you know how many W should have been produced?
- Chilton, Saperstein, Shrauner [PR**148**, 1380 (1966)] emphasized the importance of the timelike form factor, which was solved by
- Y. Yamaguchi [Nuovo Cimento **43**, 193 (1966)] Timelike form factor can be found by measuring the number of lepton pairs e^+e^- or $\mu^+\mu^-$ "massive virtual photons" of the same invariant mass; BUT the individual leptons from these electromagnetically produced pairs might mask the leptons from the $W^{\pm}$.
- This set off a spate of single and di-lepton experiments, notably the discovery by Lederman et al of "Drell-Yan" production at the BNL-AGS, E70 at FNAL and CCR at the CERN-ISR.

AGS-1969-71 Discovery of ‘Drell-Yan’ and ??



$p+U \rightarrow \mu^+\mu^- + X$

$\sqrt{s_{NN}}=7.4$ GeV



VIEW LETTERS 4 JANUARY 1971

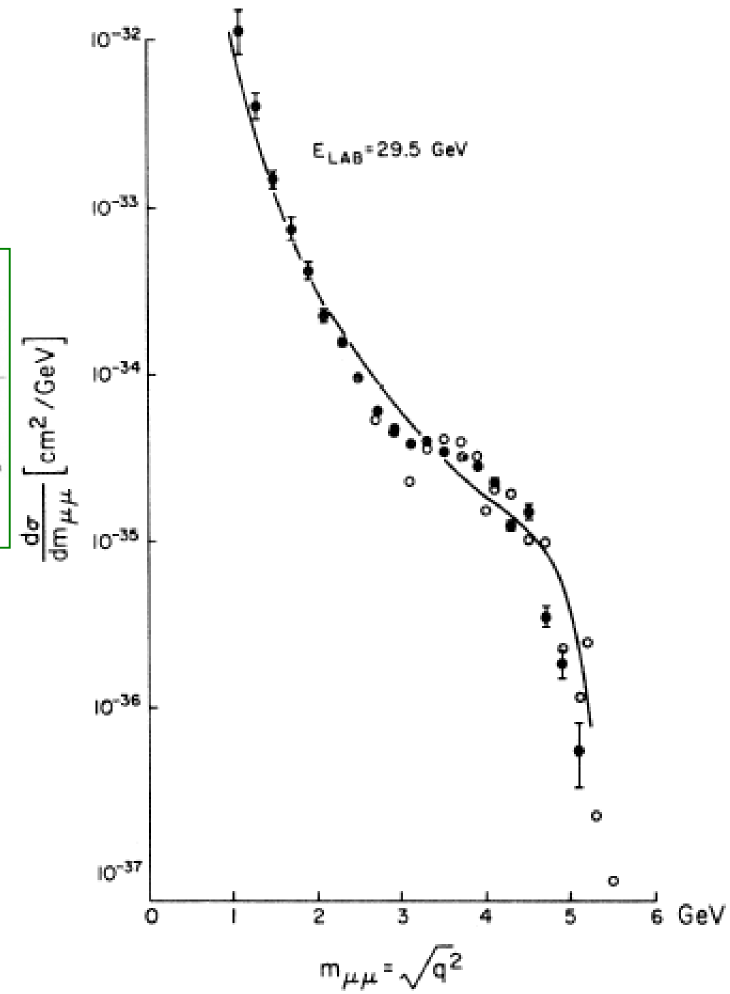


FIG. 2. Experimental cross section of Christenson *et al.*, Ref. 8.

long forgotten

Christenson, Lederman…PRL **25**, 1523 (1970)

\`Theory’ Altarelli, Brant Preparata PRL **26** 42 (1971)

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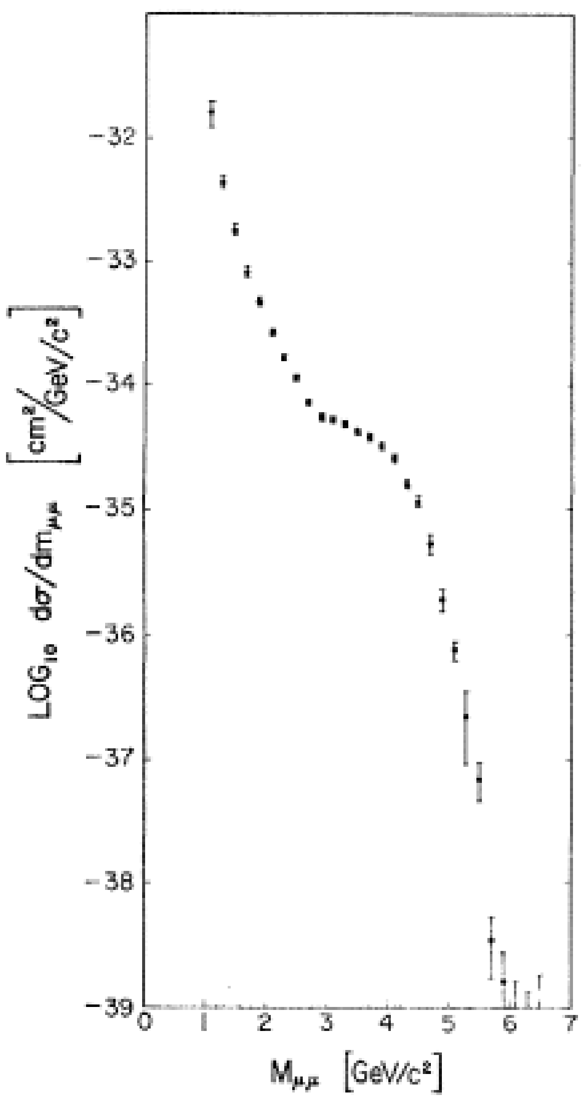
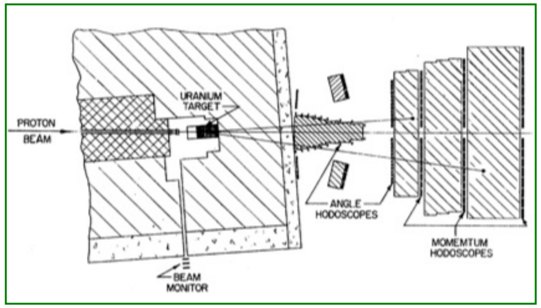


$$q+\bar{q} \rightarrow \mu^{+} + \mu^{-}$$

p+U→μ$^+$μ$^-$+X

√s$_{NN}$=7.4 GeV



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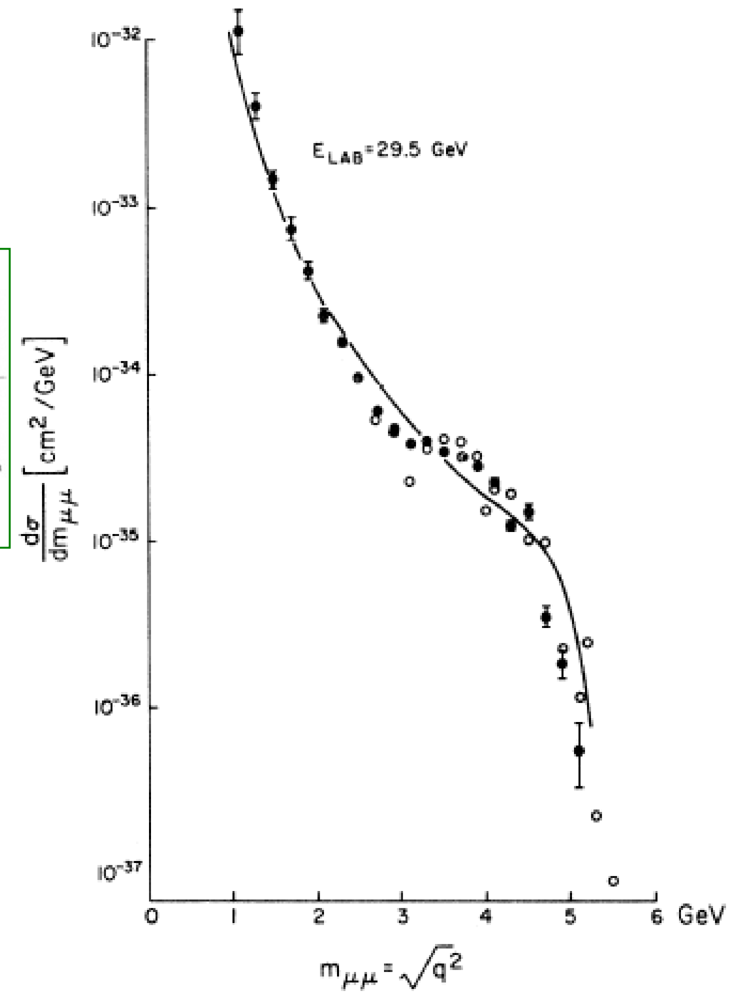

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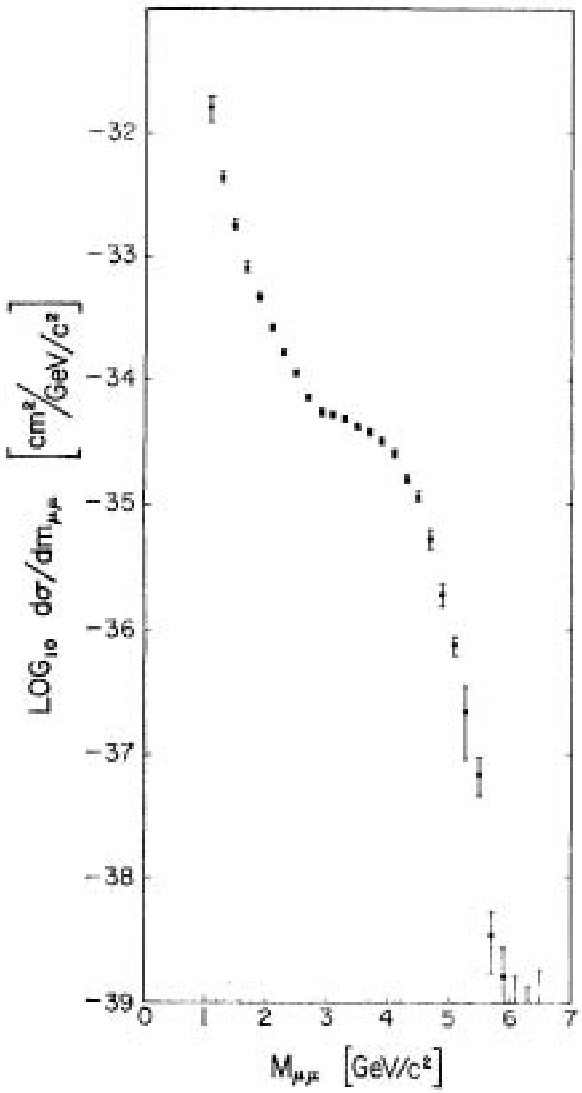

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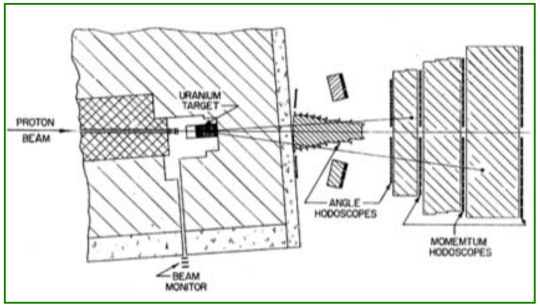
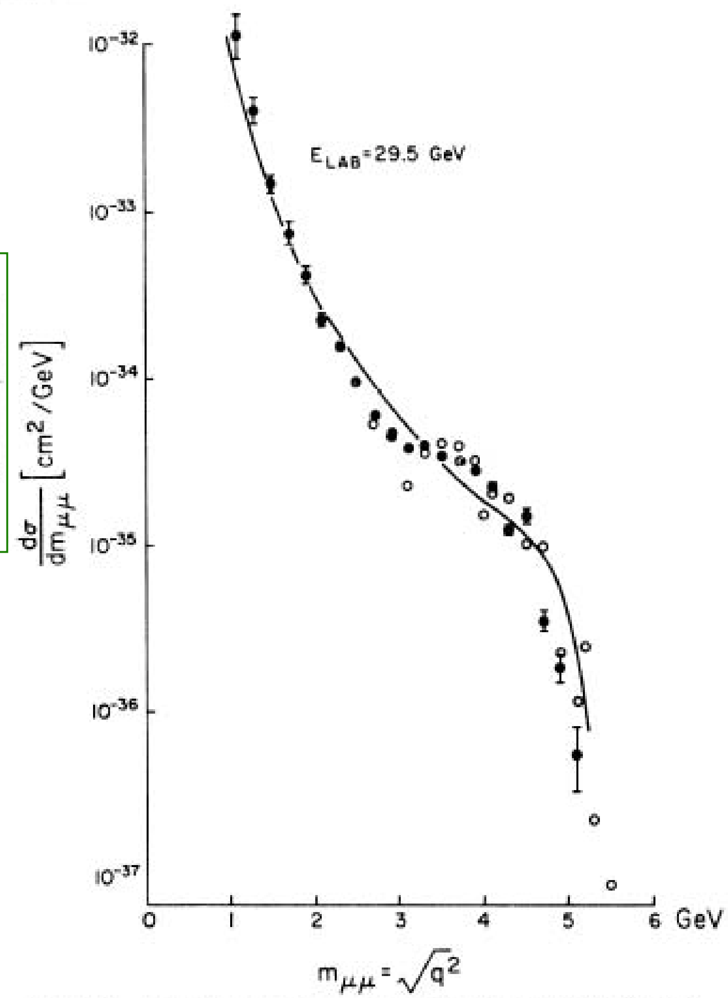


This is why I NEVER plot theory curves on any of my data

VIEW LETTERS 4 JANUARY 1971



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LML very excited in 1970: AGS-diμ continuum +Bj scaling→W cross section at any √s

Proposal to The National Accelerator Laboratory

E70-(F)NAL

"Study of Lepton Pairs from Proton-Nuclear Interactions; Search for Intermediate Bosons and Lee-Wick Structure"

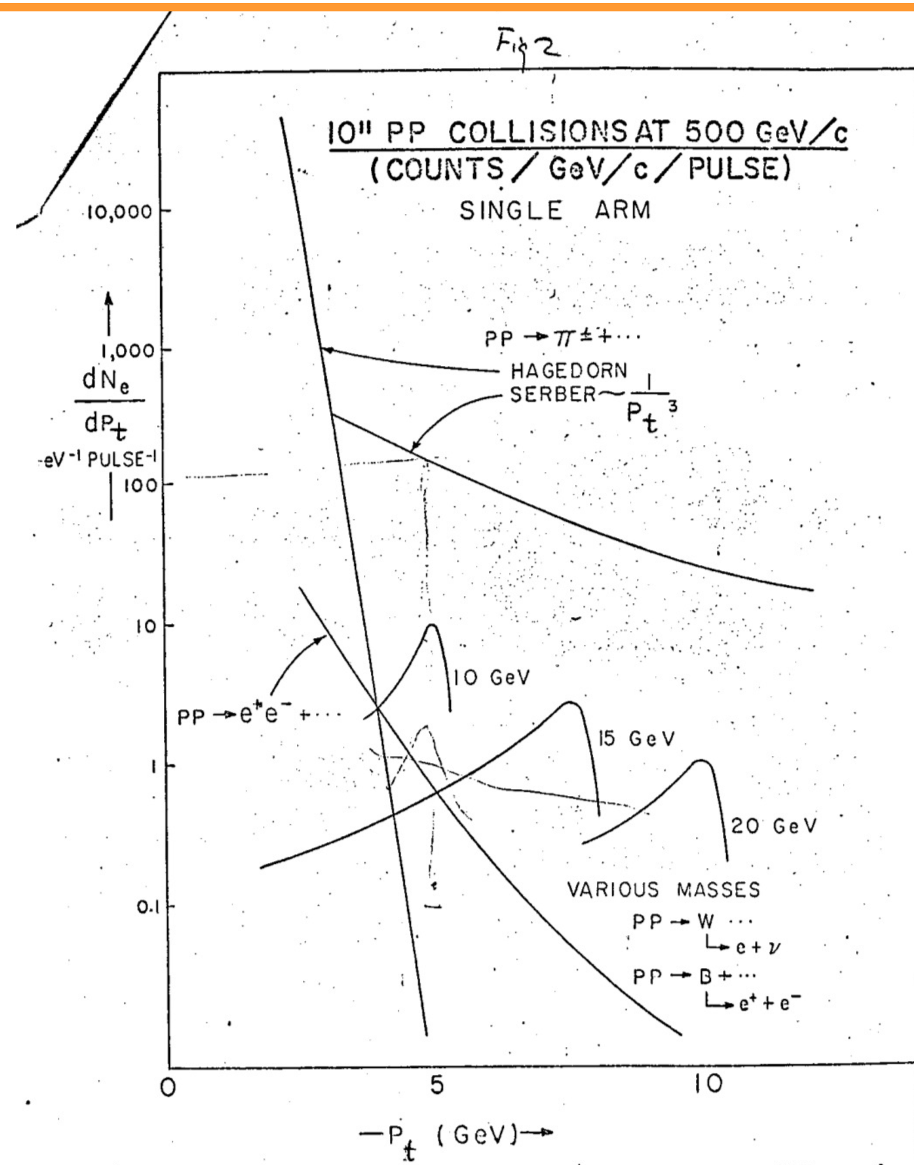
W. LEE, L.M. LEDERMAN, J. APPEL, Columbia University, M. TANNENBAUM, Harvard University, L. READ, J. SCULLI, T. WHITE, and T. YAMANOUCHI, National Accelerator Laboratory.

ABSTRACT

We propose to observe lepton pairs emerging from high energy proton-nuclear collisions. Large effective mass pairs probe the hadronic electromagnetic structure. The continuum mass spectrum will be measured and any resonant structures in the mass range up to ~ 28 GeV will be detected with great sensitivity. The data provides a prediction, via Conserved Vector Current theory, for the production cross section for weak vector bosons and these are also sought in the mass range ~8-25 GeV. We also propose an initial photon-electron beam survey at high transverse momentum which is also a W-search with good sensitivity.

June 17, 1970 + addendum Dec 1970 →

Correspondent: L. M. Lederman, Columbia University



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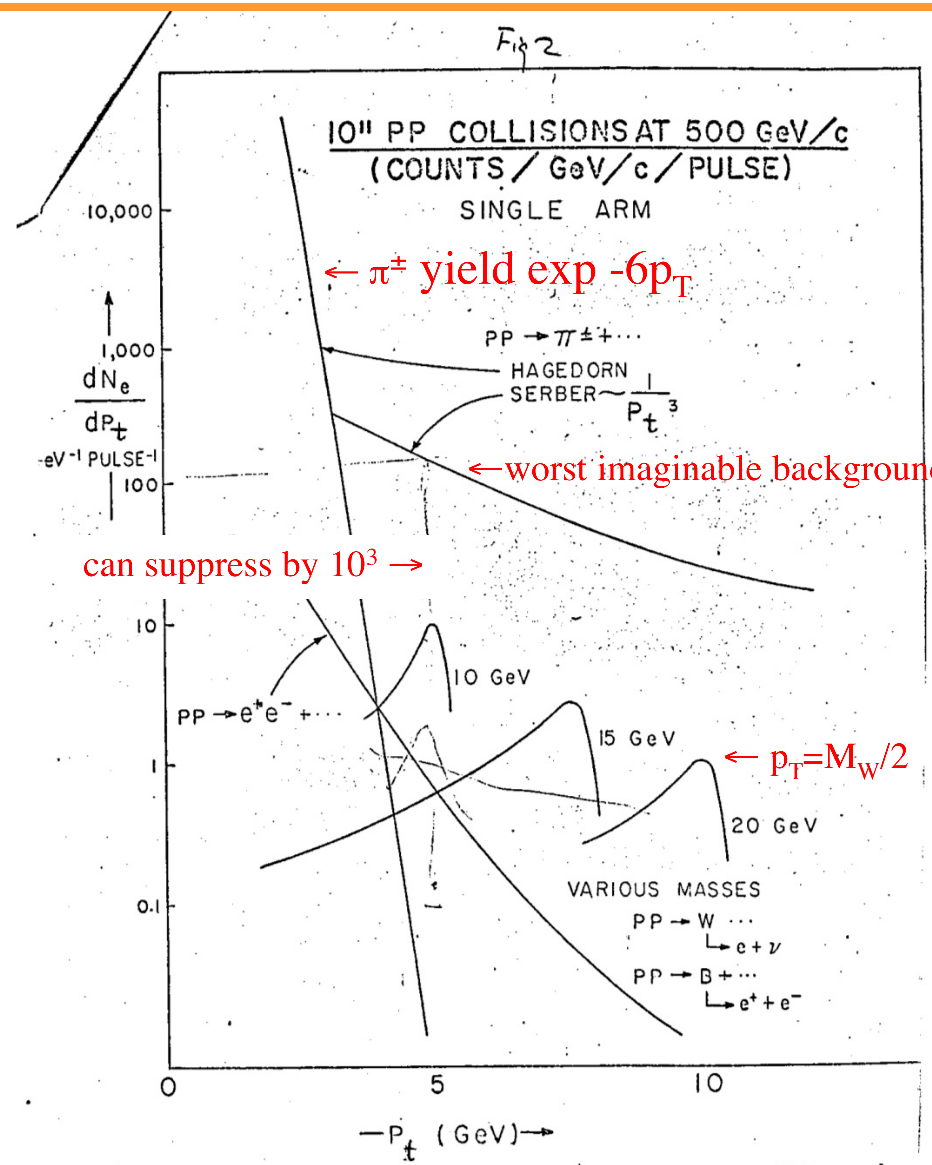


BBK 1971

S.M.Berman, J.D.Bjorken and J.B.Kogut, Phys. Rev. **D4**, 3388 (1971)

- BBK calculated for p+p collisions, the inclusive reaction

$$A+B \rightarrow C + X \qquad \text{when particle } C \text{ has } p_T \gg 1 \text{ GeV/c}$$

  - The charged partons of DIS **must scatter electromagnetically** *"which may be viewed as a* **lower bound** *on the real cross section at large p_T."*

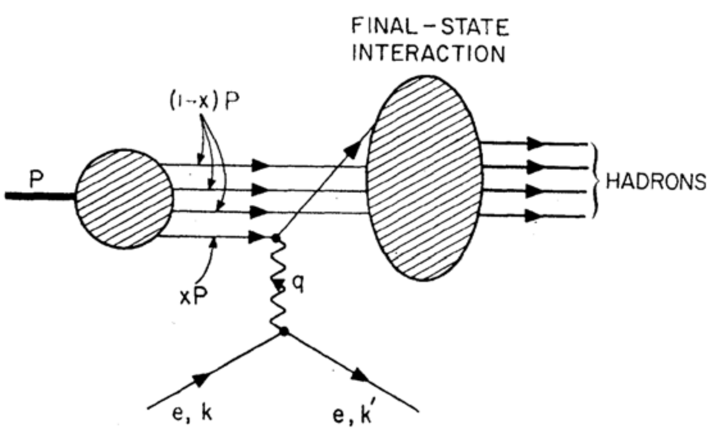
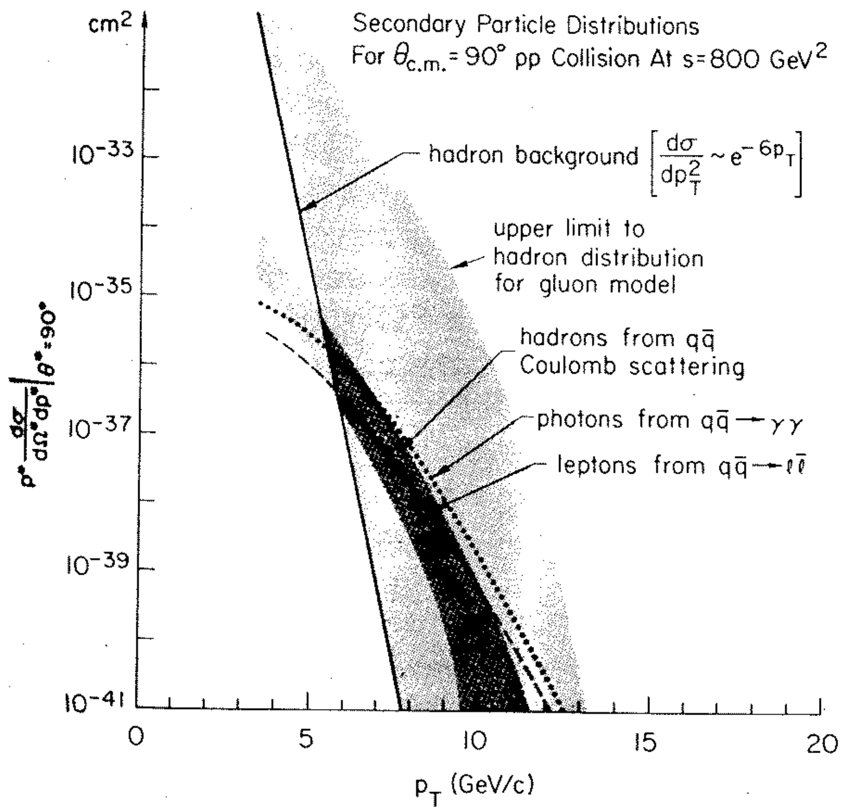


FIG. 1. Kinematics of lepton-nucleon scattering in the parton model.



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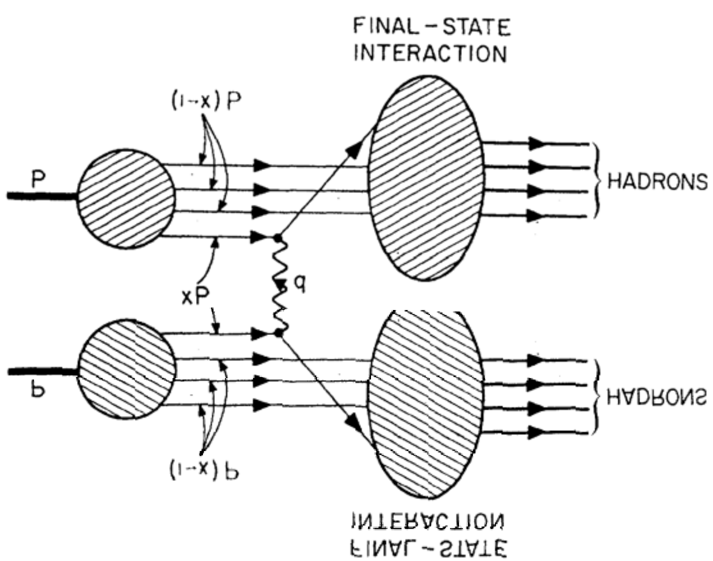
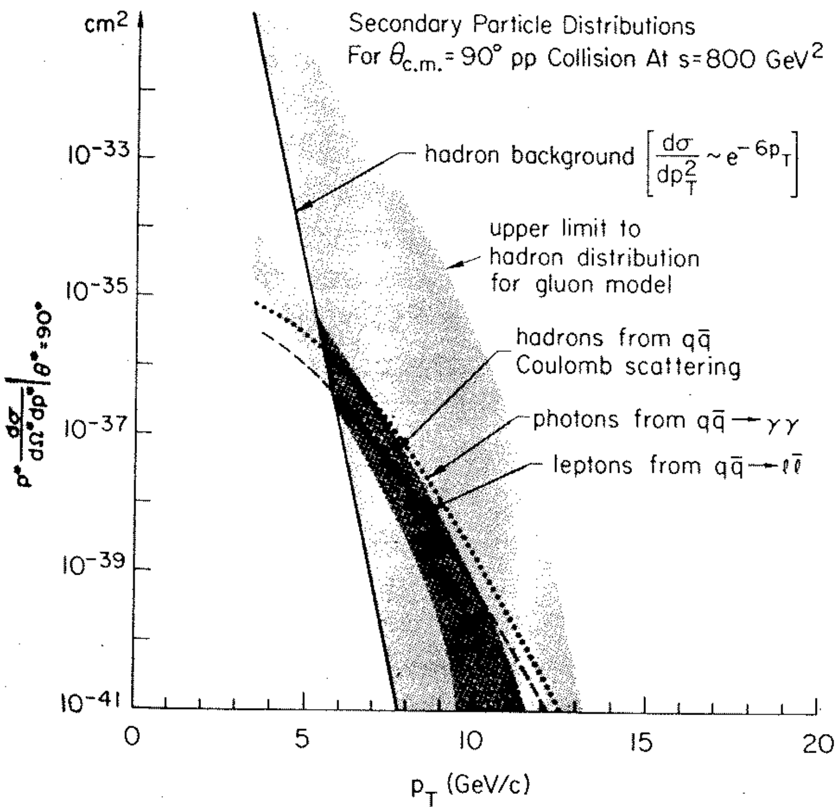




BBK 1971-continued: the era of SCALING

♡ BBK propose a **General Form** for high p_T cross sections, for the **EM** scattering, which must exist:

$$E\frac{d^3\sigma}{dp^3} = \frac{4\pi\alpha^2}{p_T^4}\mathcal{F}(x_1 = \frac{-\hat{u}}{\hat{s}}, x_2 = \frac{-\hat{t}}{\hat{s}}) \qquad (4)$$

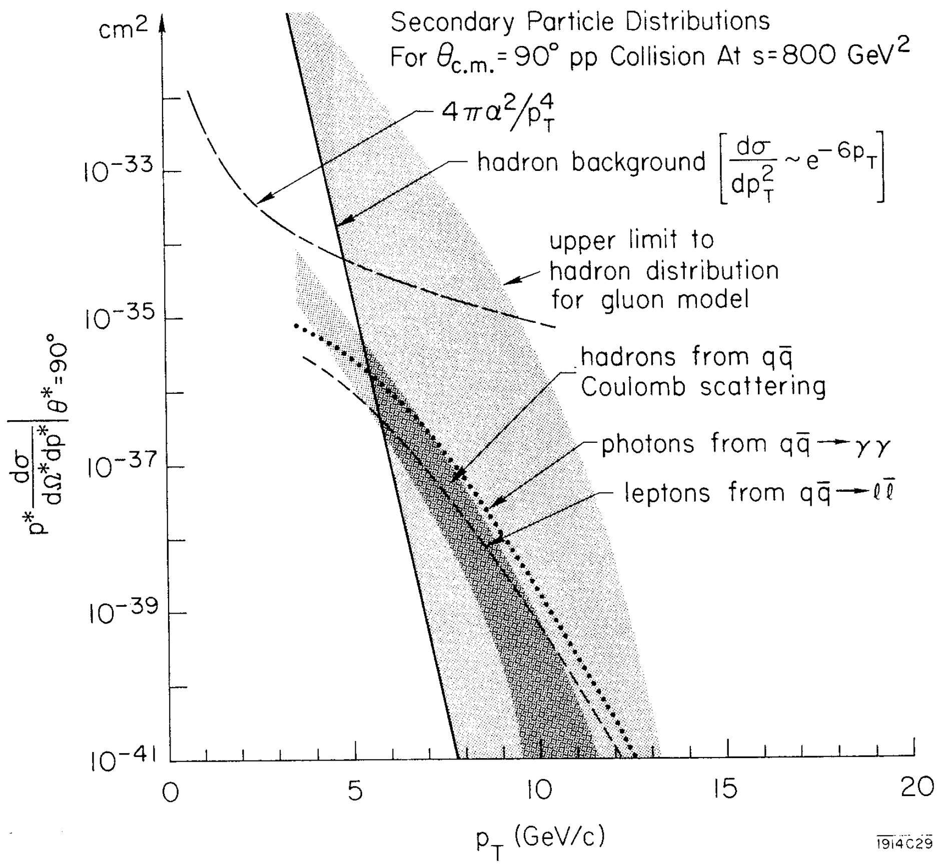
♡ The two factors are a $1/p_T^4$ term, characteristic of single photon exchange and a form factor $\mathcal{F}$

♡ Note that $x_{1,2}$ are not $x_{\rm BJ}$

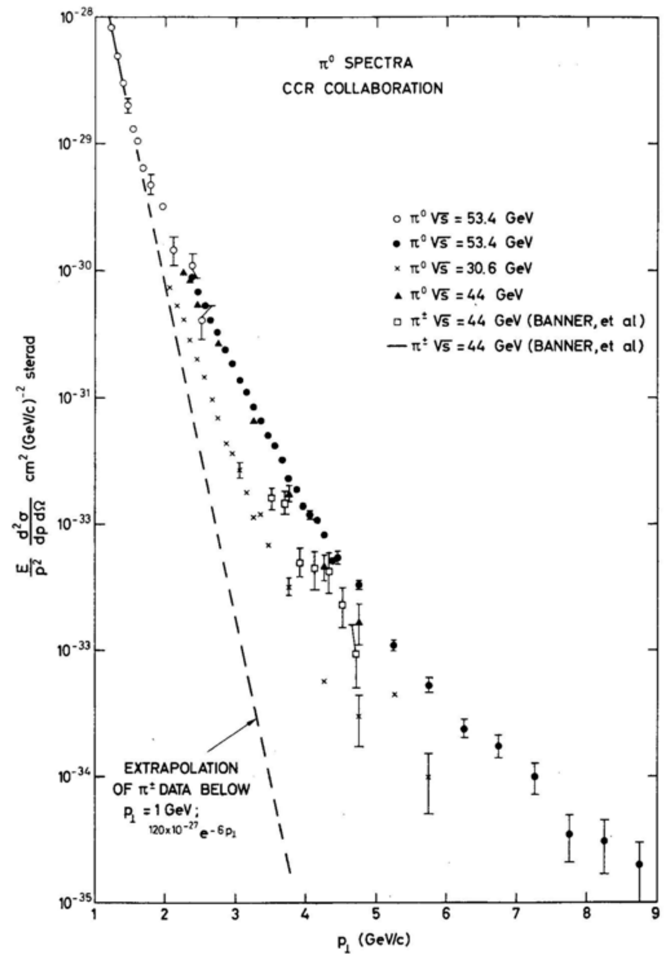
□ The point is that $\mathcal{F}$ **scales**, i.e. is only a function of the ratio of momenta.

♡ Vector ($J = 1$) Gluon exchange gives the same form as Eq. 4 but much larger.

Bj-prediction 1971 CCR discovery 1972



Bjorken-International Lepton-Photon Cornell 1971-see discussion of Bj with Feynman about whether partons are hard (Bj) or soft (Feynman) pp.296-7



CCR, R. Cool, ICHEP 1972
parton-parton scattering >> EM

Kuti-Weisskopf 1971: "The partons are identified with quarks"

PHYSICAL REVIEW D VOLUME 4, NUMBER 11 1 DECEMBER 1971

Inelastic Lepton-Nucleon Scattering and Lepton Pair Production in the Relativistic Quark-Parton Model*

Julius Kuti† and Victor F. Weisskopf
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 26 July 1971)

We discuss the interaction of hadrons with leptons in the limit of large momentum transfer. A special parton model will be used for the hadrons in which the partons are identified with quarks. The relativistic quark model with which we interpret recent observations is formulated as follows: (1) The baryons are composed of three valence quarks and a core of an indefinite number of quark-antiquark pairs. (2) The lepton "sees" the nucleon in the limit of large momenta in the c.m. frame as an assembly of freely moving constituents with point charges. (3) The scattering of the valence quarks is interpreted as the nondiffractive com-

This model is used to calculate the deep-inelastic scattering of electrons by protons and neutrons and its dependence on the relative spin orientations, the inelastic scattering of neutrinos by nucleons, and the creation of massive muon pairs by proton-proton collisions. After adjusting the open constant to the data of electron-

Kuti-Weisskopf 1971:
"The partons are identified with quarks"

3432 J. KUTI AND V.

PHYSICAL REVIEW D 1 DECEMBER 1971

Inelastic Leptor ... **oduction**
in ...

Laboratory for Nuclear Sc ... *ıte of Technology,*

We discuss the intera ... ntum transfer.
A special parton model ... entified with
quarks. The relativisti ... ons is form-
ulated as follows: (1) Tl ... core of an
indefinite number of qu ... in the limit
of large momenta in the ... ıts with point
charges. (3) The scatte ... ractive com-

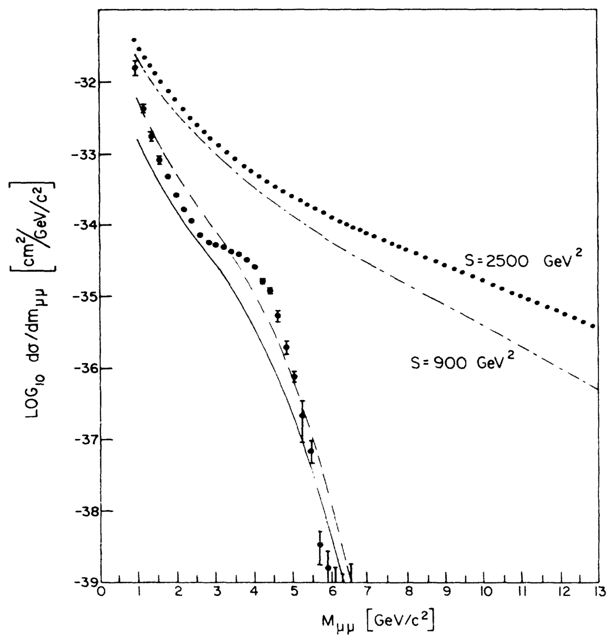


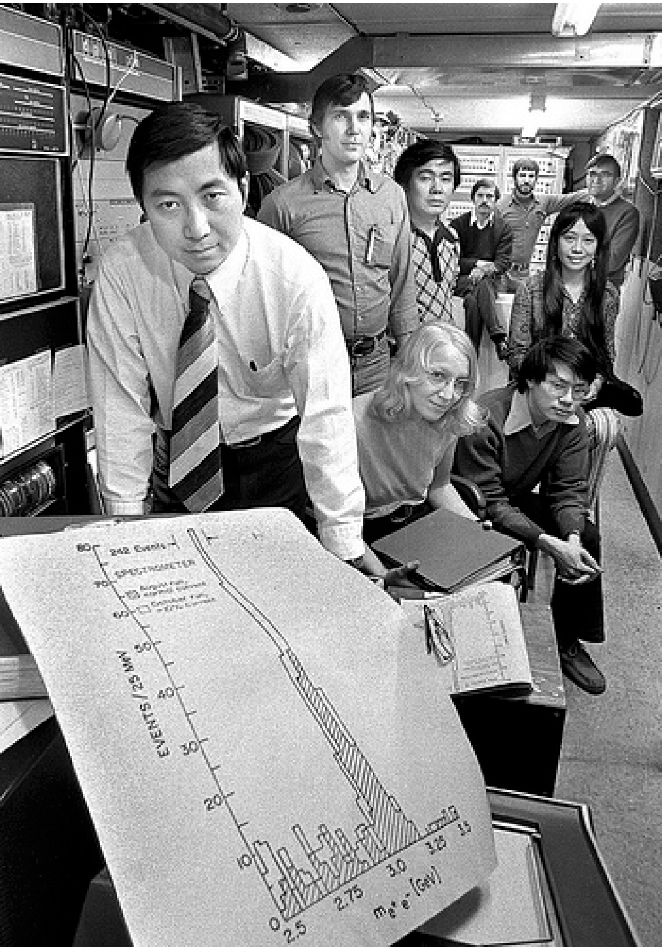
FIG. 6. The $\mu^+\mu^-$ pair production cross section as a function of the invariant mass of the $\mu^+\mu^-$ pair. The solid line is $g=1$, the dashed line is $g=3$. The dotted line corresponds to $s=2500$ (GeV)^2, the dashed-dotted one is $s=900$ (GeV)^2; both are plotted with $g=1$.

In notation we follow Bjorken and Paschos, who have derived general sum rules in the framework of the parton model.

tering of electrons by protons ... the deep-inelastic scat-
tations, the inelastic scatteri ... relative spin orien-
pairs by proton-proton collisi ... ation of massive muon
... o the data of electron-

n.b. this is a $q+\bar{q}\rightarrow\mu^{+}+\mu^{-}$ reaction which is electromagnetic. There is no discussion of whether quarks might interact other than by electromagnetic scattering.

?? explained by J/ψ in 1974 at AGS + SLAC



J/ψ is a bound state of $c-\bar{c}$, where c is Glashow's 4th quark, the charm quark.

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu

Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee

Brookhaven National Laboratory, Upton, New York 11973

(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \to e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

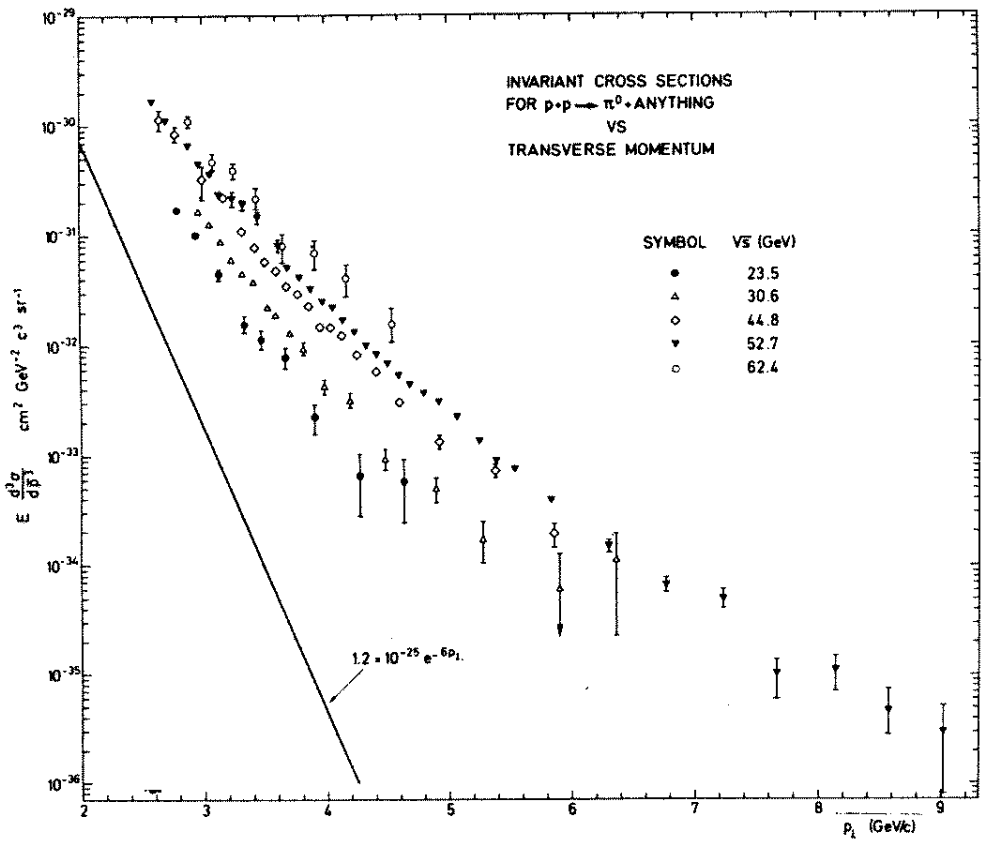
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Now, Back To High p_T "Hard-Scattering"

CCR at the CERN-ISR(1973): Publication of Discovery of high p_T π^0 production in p-p



F.W. Büsser, *et al.*,
CERN, Columbia, Rockefeller Collaboration
Phys. Lett. **46B**, 471 (1973)

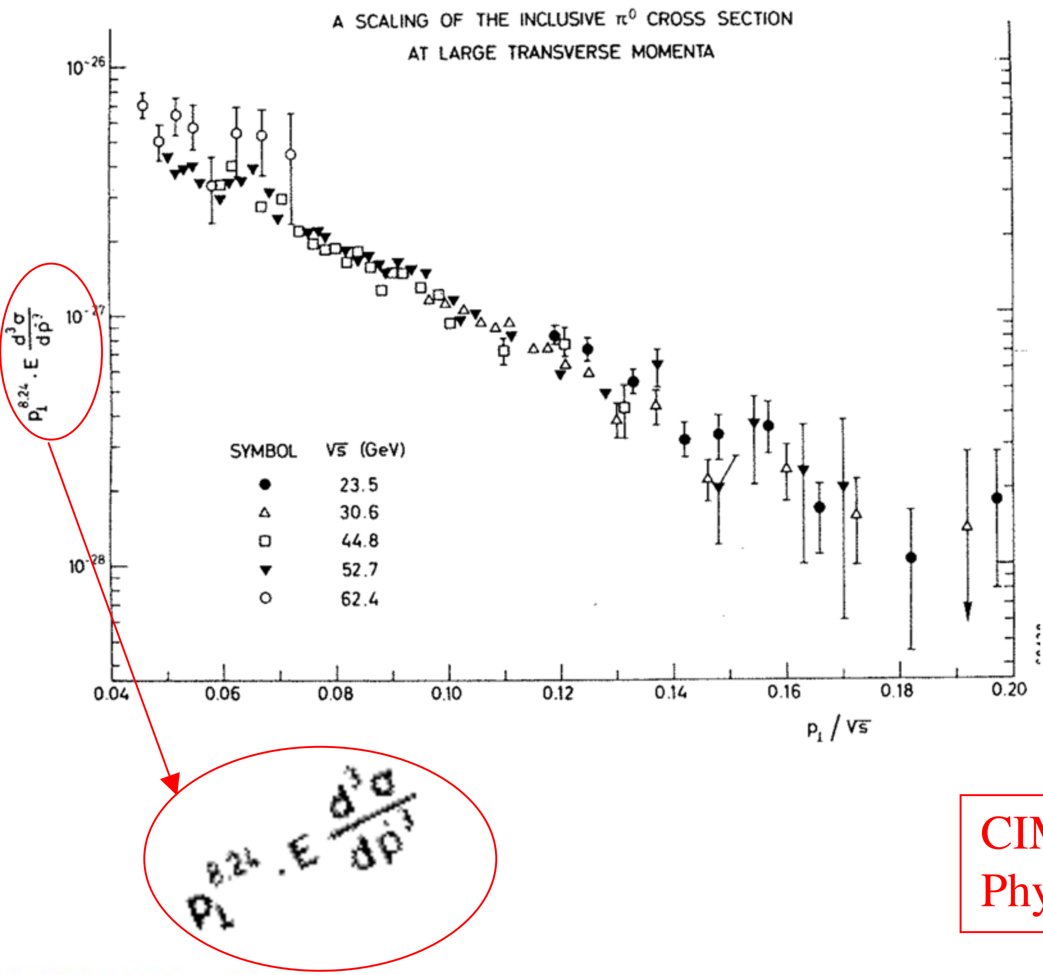
Bjorken scaling PR**179**(1969)1547 →
Berman**B**j**K**ogut scaling PRD4(71)3388
→ **B**lankenbecler, **B**rodsky, **G**union
$x_T=2p_T/\sqrt{s}$ Scaling PL **42B**, 461 (1972)

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{n_{\rm eff}}} F\left(\frac{p_T}{\sqrt{s}}\right) = \frac{1}{\sqrt{s}^{\,n_{\rm eff}}} G(x_T)$$

$n_{\rm eff}$ gives the form of the force-law between constituents: $n_{\rm eff}$=4 for QED

- e^{-6p_T} breaks to a power law at high p_T with characteristic √s (c.m. energy) dependence
- Large rate indicates that partons interact strongly (>> EM) with other.
- Data follow $x_T=2p_T/\sqrt{s}$ scaling but with $n_{\rm eff}$=8!, not $n_{\rm eff}$=4 as expected for QED

x_T scaling with n=8, not 4 Inspires Constituent Interchange Model



$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^n} F\left(\frac{p_T}{\sqrt{s}}\right)$$

$x_T = 2p_T/\sqrt{s}$

n=4 for QED or vector gluon

n=8 for quark-meson scattering by the exchange of a quark

CIM-Blankenbecler, Brodsky, Gunion, Phys.Lett.**42B**,461(1972)

Constituent Interchange Model

Blankenbecler, Brodsky, Gunion, *Inclusive Processes at High Transverse Momentum*, Phys. Lett. **42B**, 461(1972)

♡ Inspired by the *dramatic features* of pion inclusive reactions revealed by "the recent measurements at CERN ISR of single-particle inclusive scattering at 90° and large transverse momentum", Blankenbecler, Brodsky and Gunion propose a new general scaling form:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{n}} F\left(\frac{p_T}{\sqrt{s}}\right) \qquad (5)$$

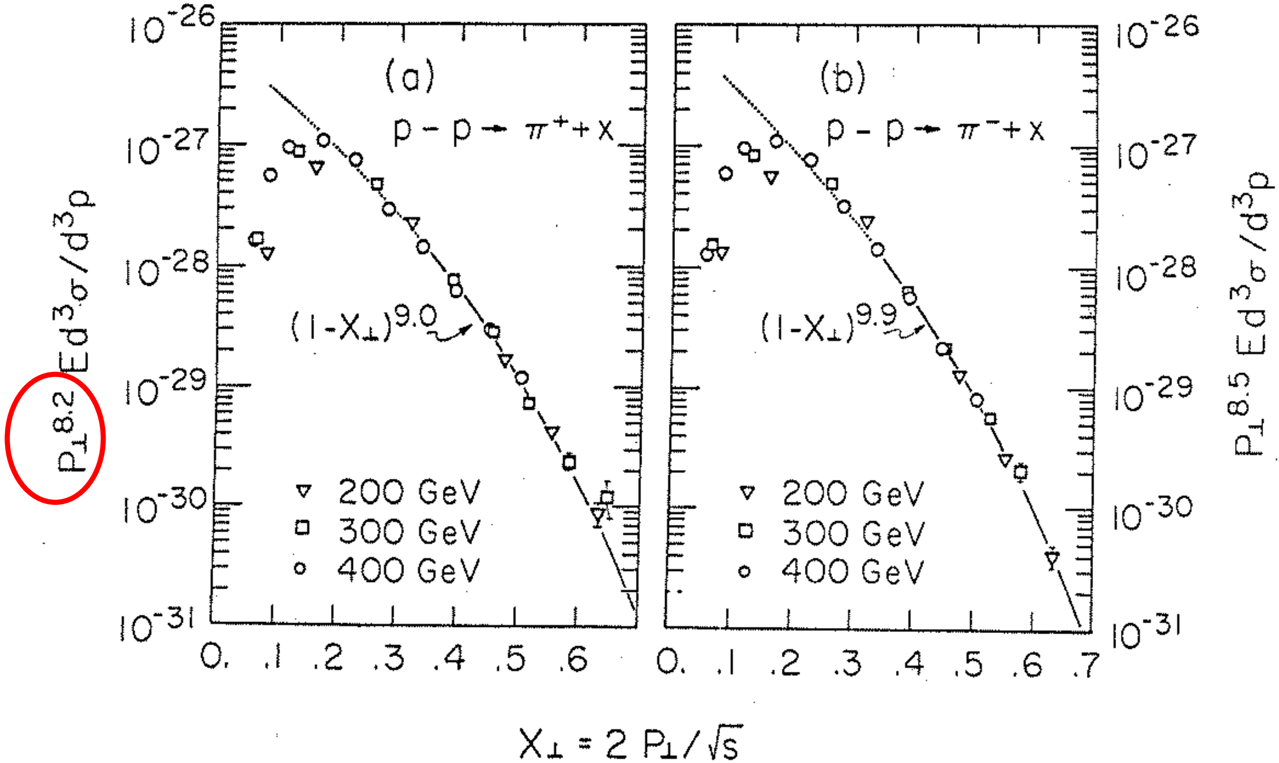
♡ n gives the form of the force-law between constituents

♡ $n = 4$ for QED or Vector Gluon

♡ Perhaps more importantly, BBG predict n=**8** for the case of quark-meson scattering by the exchange of a quark, **C.I.M.**, as apparently observed.

State of the Art
Fermilab 1977 $\sqrt{s} \leq 27.4$ GeV

D. Antreasyan, J. Cronin, et al., PRL **38**, 112 (1977)



Beautiful x_T scaling at all 3 fixed target energies with n=8

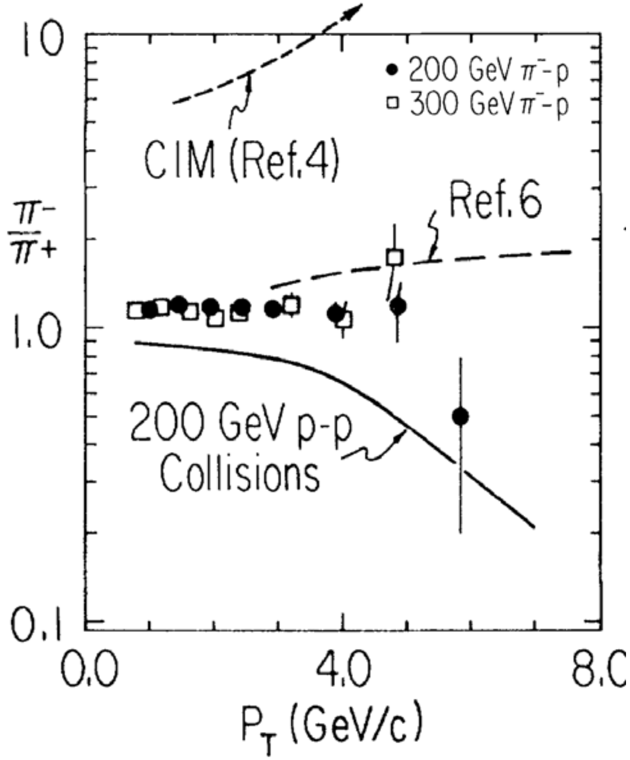
Totally Misleading--Not CIM or QCD but k_T

p.s. Fermilab experiment (1980) kills CIM

H. J. Frisch, et al., PRL **44**, 511 (1980) $\pi^- + p \rightarrow \pi^\pm + X$

If quark-meson scattering by exchange of a quark dominates then π^- should dominate π^+ at large p_T

I put this and previous slide in only because Stan Brodsky was at 40th QCD Conference and he still believes in CIM



Statement in Brodsky et al,PLB**637**, 58 (2006):"We find that high-p_T hadrons are produced by different mechanisms at fixed-target and collider energies. For pions, higher-twist subprocesses where the pion is produced directly dominate at fixed target energy," is contradicted by this measurement. Also see Anne & Stan PRL105, 062002(2010).

First prediction using 'QCD' 1975

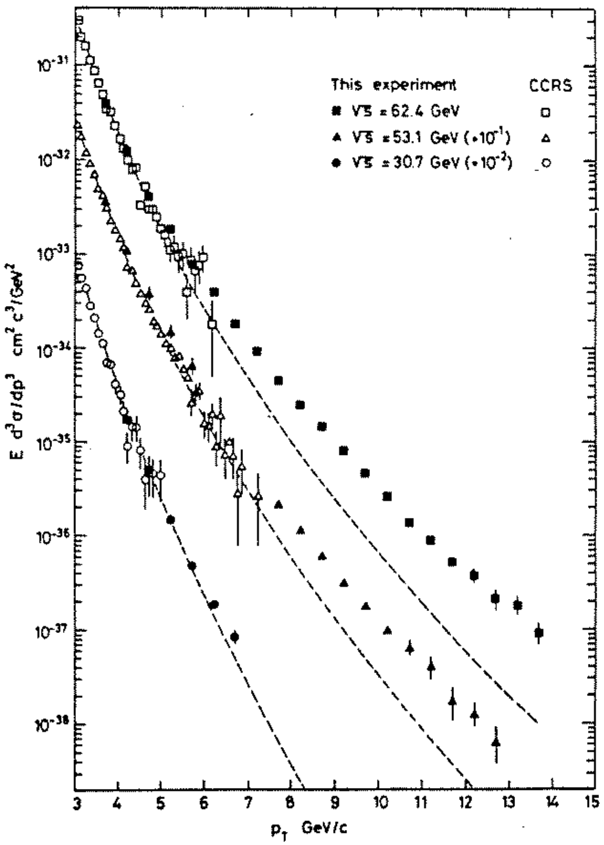
R. F. Cahalan, K. A. Geer, J. Kogut and Leonard Susskind, Phys. Rev. **D11**, 1199 (1975)

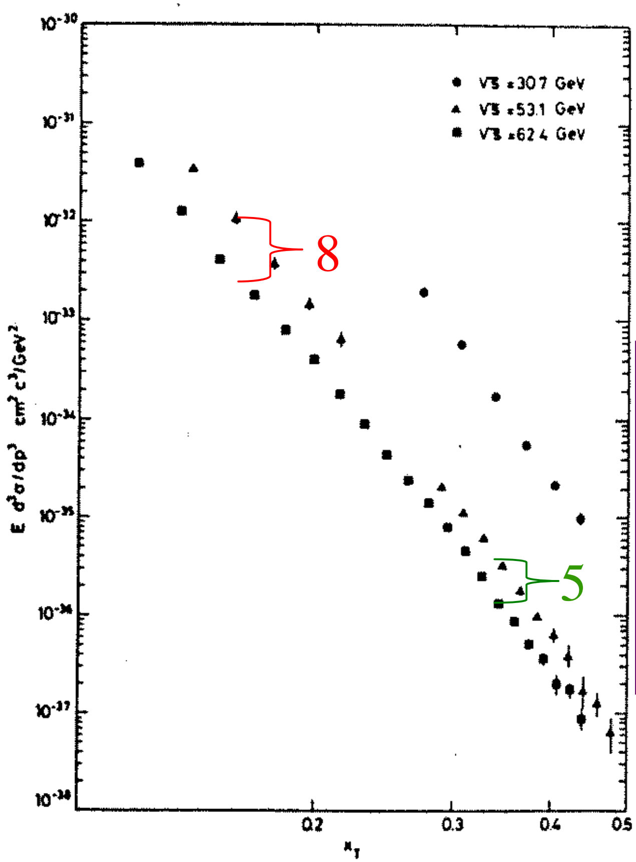
"Asymptotic freedom and the "absence" of vector-gluon exchange in wide-angle hadronic collisions"

- **Abstract:** The naive, pointlike parton model of Berman, Bjorken and Kogut is generalized to scale-invariant and asymptotically free field theories. The asymptotically free field generalization is studied in detail. Although such theories contain vector fields, single vector-gluon exchange contributes insignificantly to wide-angle hadronic collisions. This follows from (1) the smallness of the invariant charge at small distances and (2) the *breakdown of naive scaling* in these theories. These effects should explain the apparent absence of vector exchange in inclusive and exclusive hadronic collisions at large momentum transfers observed at Fermilab and at the CERN ISR.
- An interesting **Acknowledgement:** ... Two of us (J. K. and L. S. also thank S. Brodsky for *emphasizing to us repeatedly* that the present data on wide-angle hadron scattering *show no evidence for vector exchange.*
- Nobody's perfect, they get *one* thing right! They introduce the "effective index" $n(x_T, \sqrt{s})$ to account for 'scale breaking':

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{n(x_T,\sqrt{s})}} F\left(\frac{p_T}{\sqrt{s}}\right) = \frac{1}{\sqrt{s}^{\,n(x_T,\sqrt{s})}} G\left(\frac{p_T}{\sqrt{s}}\right)$$

CCOR 1978--Discovery of "REALLY high p_T>7 GeV/c" at ISR





CCOR A.L.S. Angelis, et al, Phys.Lett. **79B**, 505 (1978)

QCD: Cahalan, Geer, Kogut, Susskind, PR**D11**, 1199 (1975)

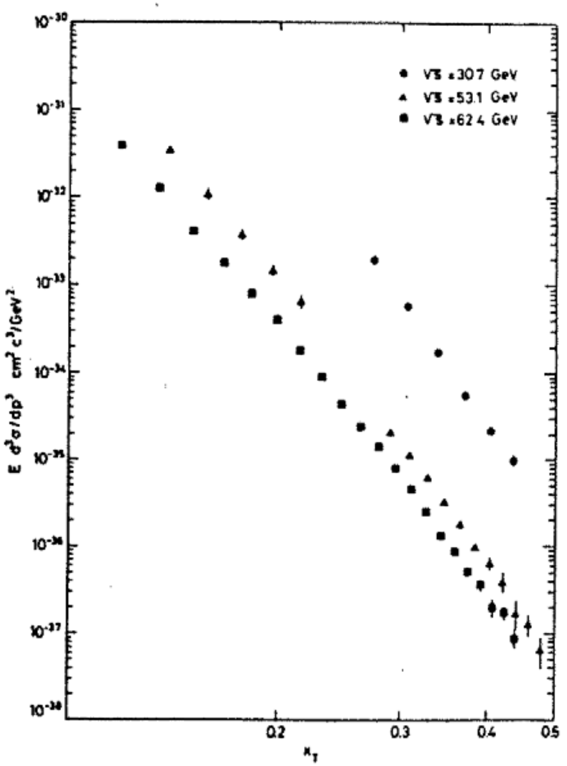
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n_{\rm eff}(x_T,\sqrt{s})}}\,G(x_T)$$

$$\left(\frac{\sqrt{s_1}}{\sqrt{s_2}}\right)^{n_{\rm eff}(x_T,\sqrt{s})} = \frac{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_2})}{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_1})}$$

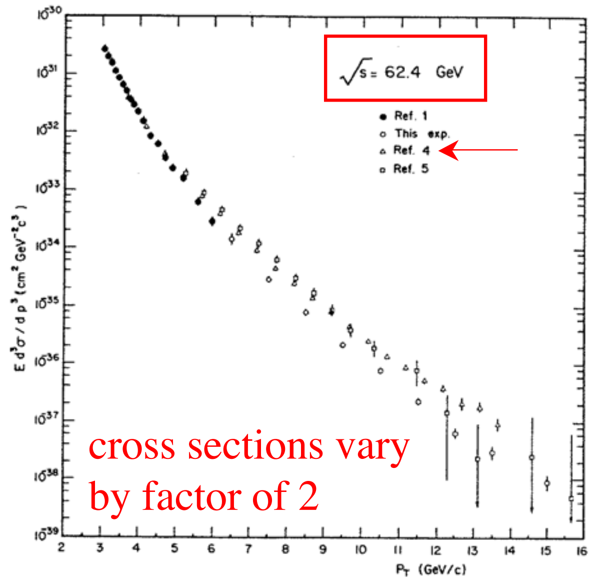
- ♡ $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1-x_T)^{12.1\pm0.6}$
  $7.5 \leq p_T \leq 14.0$ GeV/c,
  $53.1 \leq \sqrt{s} \leq 62.4$ GeV
  (including *all* systematic errors).

$n_{\rm eff}$=5 (=4^{++}) as predicted for QCD

1978-$n_{eff}(x_T, \sqrt{s})$ WORKS $n_{eff} \rightarrow 5 = 4^{++}$

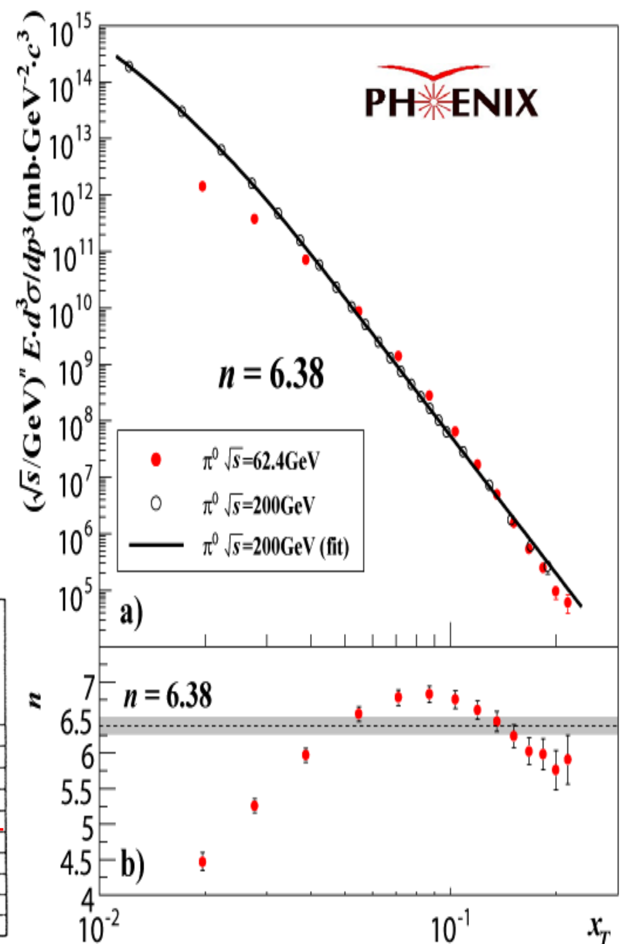


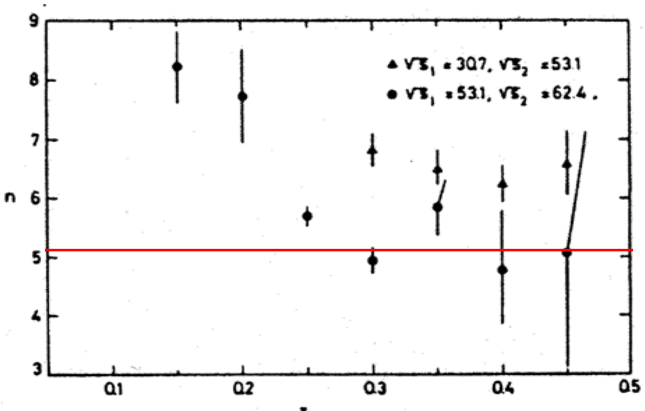
C.Kourkoumelis, et al
Phys.Lett. **84B**, 279 (1979)



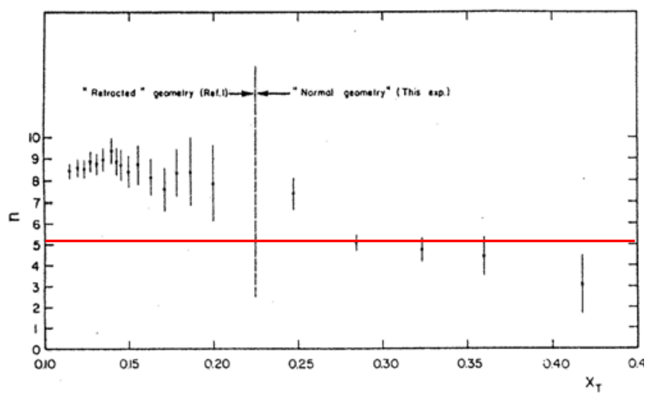
cross sections vary
by factor of 2

A.Adare, et al, PHENIX
PRD**79** (2009) 012003

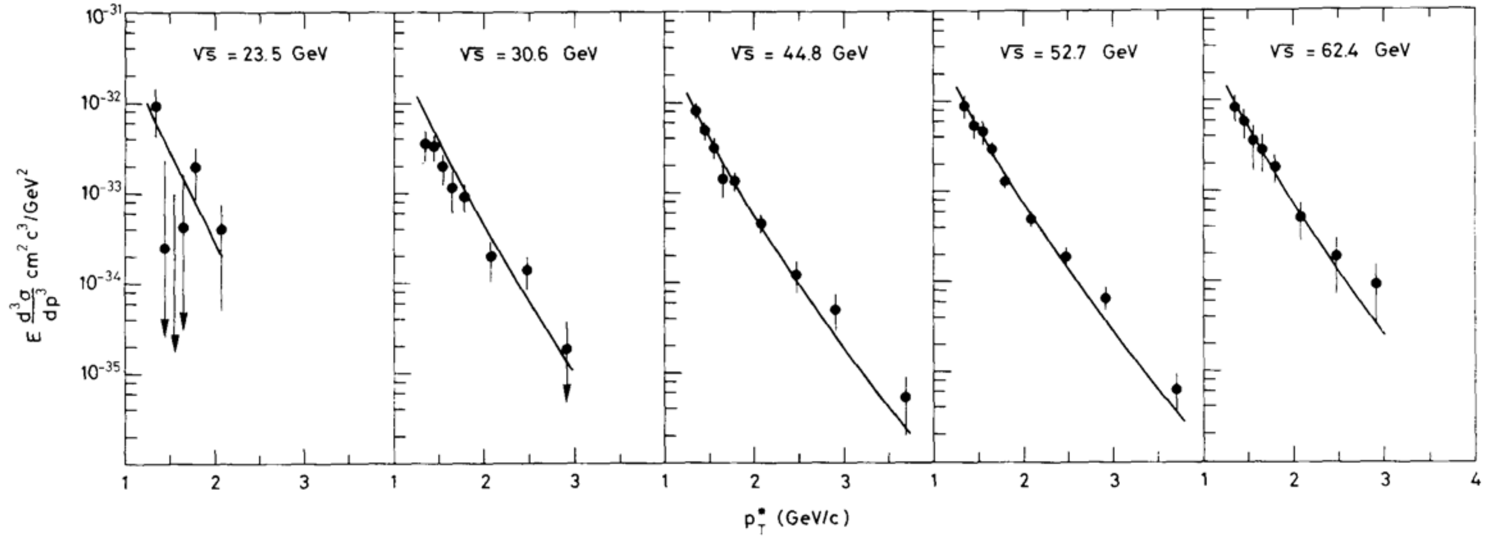




But $n(x_T, \sqrt{s})$ agrees



CCRS-1974 Discovery of direct $e^{\pm}\sim10^{-4}\pi^{\pm}$ at ISR not due to internal conversion of direct photons



CCRS PLB**53**(1974)212; NPB**113**(1976)189

Data points $(e^+ + e^-)/2$ lines $10^{-4}\,(\pi^+ + \pi^-)/2$

- Farrar and Frautschi PRL**36**(1976)1017 proposed that direct leptons are due to internal conversion of direct photons with $\gamma/\pi\sim$10-20% to e^+e^- ($d\sigma/dm\sim1/m$) for p_T>1.3 GeV/c. CCRS looks, finds very few events, sets limits excluding this.

95% confidence level upper limits for a particle of mass m, or a mass continuum, which decays to e^+e^- with branching ratio B, at $\sqrt{s}$ = 52.7 GeV/c

Mass (GeV/c^2)	$B\frac{d\sigma}{dy}(p_T^* > 1.3$ GeV/c) (cm^2)	Fraction of single electron signal
0.400	5.54×10^{-33}	0.064
0.500	8.37×10^{-33}	0.104
0.600	1.64×10^{-32}	0.178

p.s. these direct $e^{\pm}$ are due to semi-leptonic decay of charm particles not discovered until 1976, 2 year later: Hinchliffe and Llewellyn-Smith NPB**114**(1976)45

J/Psi and direct e± at the CERN-ISR

First

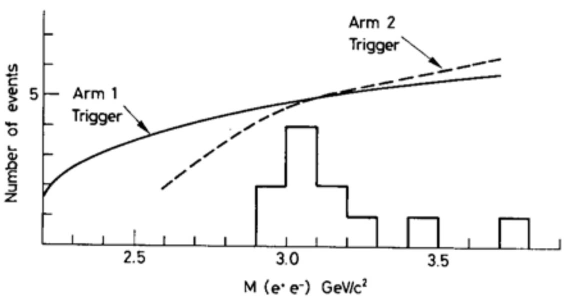


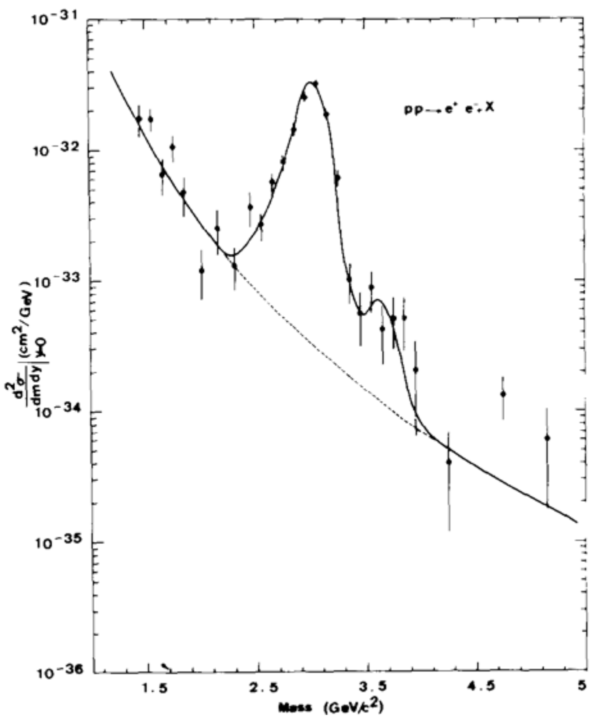
FIG. 2

Fig. 2. Invariant mass distribution for the observed e^+e^- pairs. The curves represent the shapes of the acceptance, as a function of the e^+e^- invariant mass value, for the Arm 1 and Arm 2 triggers, respectively.

CCRS PLB**56**(1975)482
2nd J/Ψ in Europe

Best

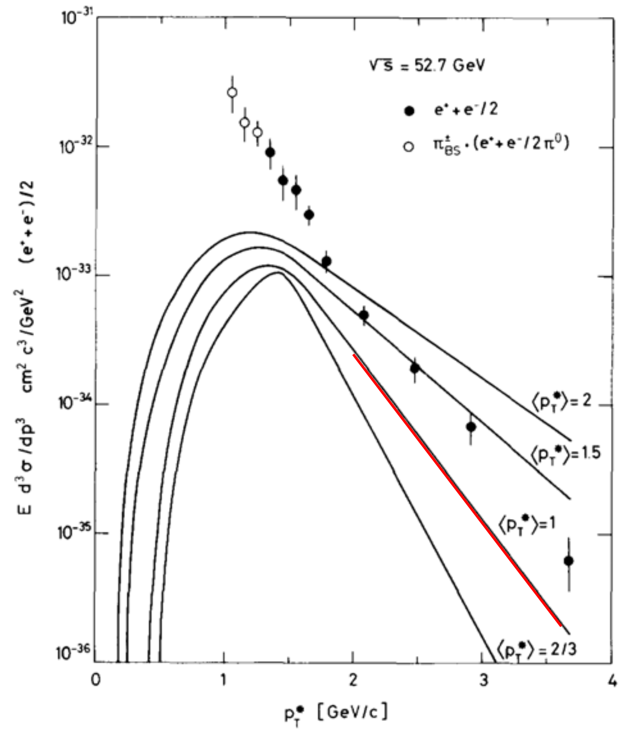
A.G. Clark et al. / Electron pair production at the ISR



CSZ NPB**142**(1978)29
$\langle p_T \rangle$=1.10±0.05 GeV/c

Not cause of direct e±

F.W. Büsser et al. / Electrons at the ISR



CCRS NPB**113**(1976)189
direct e± not due to J/Ψ

Strangeness 1996 Budapest

APH N.S., Heavy Ion Physics 4 (1996) 139-148

HEAVY ION PHYSICS

Charm in PHENIX—a signal or a background?

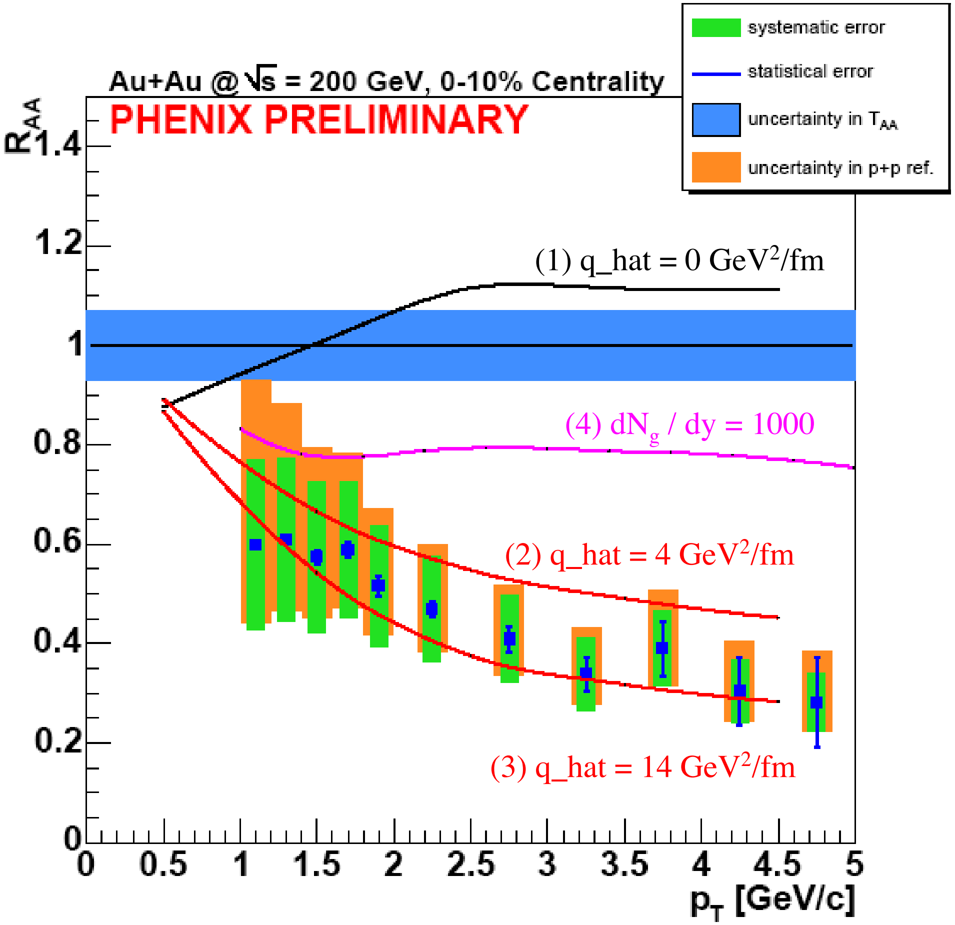
M. J. Tannenbaum

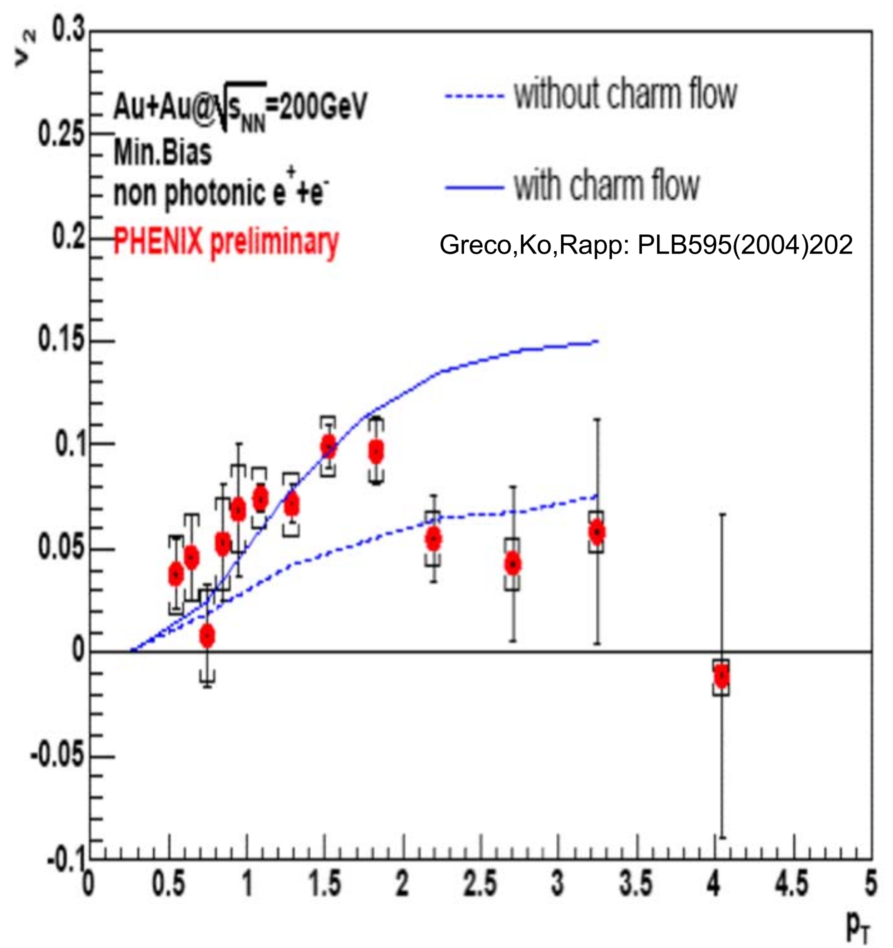
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

Received 26 June 1996

Abstract. Charm, as well as Strangeness, plays an important role in searches for the Quark Gluon Plasma. J/Ψ Suppression and Strangeness Enhancement are two of the earliest proposed QGP signatures. Recent theoretical work on charm in Relativistic Heavy Ion collisions has focussed on dilepton production. However, even before the discovery of the J/Ψ, evidence of open charm was seen in hadron collisions via the observation of prompt **single** leptons "resulting from the semi-leptonic decays of charm particles."[1] The 'copious' yield of direct (i.e. not from Dalitz decays) single electrons and muons—at a level $e/\pi \sim 10^{-4}$ for $p_T \geq 1.3$ GeV/c—observed in the early 1970's was explained by Hinchliffe and Llewellyn-Smith and Bourquin and Gaillard as evidence of open-charm production. It is likely that e/π at RHIC is large and is a good measure of charm production. Thus, a measurement of single electrons with moderate $p_T > 1.5$ GeV/c at RHIC should give a clean charm signal in heavy ion collisions, **with no combinatoric background.**

→Quark Matter 2005-RHIC-single e± in AuAu





Single e± from heavy quark decay suppressed as much as π^0 from light quarks; and they flow. Disfavors radiative energy loss

Theory curves
(1-3) from N. Armesto, *et al.*, PRD 71, 054027

(4) from M. Djordjevic, M. Gyulassy, S.Wicks, PRL 94, 112301

Major Discovery---still not understood in 2012

QCD Direct photon production-simple theory hard experiment

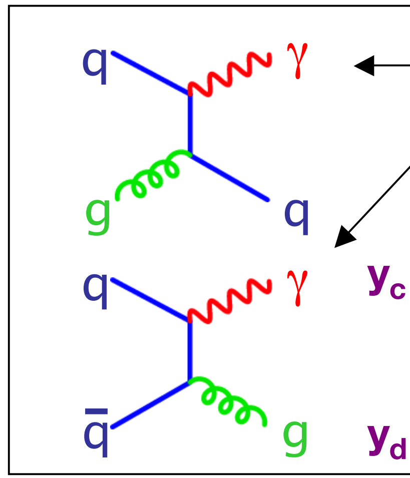
See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320

$A+B \rightarrow \gamma + X$

Compton

Annihilation

small-ignore



isolated photons

q is 8/1 u/d quark in p+p

y=-ln tan θ /2 (rapidity)

θ * is in q+g c.m system

Analytical formula for γ-jet cross section for a photon at p_T, y_c (and *parton* (jet) at p_T, y_d):

$$\frac{d^3\sigma}{dp_T^2\, dy_c\, dy_d} = x_1\, g_A(x_1, Q^2)\, F_{2B}(x_2, Q^2) \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2} \left(\frac{1+\cos\theta^*}{2} + \frac{2}{1+\cos\theta^*} \right)$$
$$+\, F_{2A}(x_1, Q^2)\, x_2\, g_B(x_2, Q^2) \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2} \left(\frac{1-\cos\theta^*}{2} + \frac{2}{1-\cos\theta^*} \right)$$

Also,the entire kinematics of the scattering can be calculated

$$\cos\theta^* = \tanh\frac{(y_c - y_d)}{2}$$

$$x_{1,2} = x_T \frac{e^{\pm y_c} + e^{\pm y_d}}{2}$$

$g(x)$ and $F_2(x)$ are g and q pdf's in nuclei A,B

The first ‘evidence’ for direct-γ was wrong; but internal conversions provided a stringent limit

- L.~Yuan, E.~Amaldi Rome, BNL, CERN PLB **77** (1978) 240 set a limit on real photons using PbGl: $\gamma/\pi^0=0.021\pm0.012$ $3.5<p_T<5.0$ GeV/c
- This corrected a **notoriously wrong** result of $\gamma/\pi^0=0.20\pm0.06\pm0.07$ for $2.8<p_T<3.8$ GeV/c also using PbGl P.Darriulat *et al*, NPB**110** (1976) 365
- The most stringent limit came from (non observation) of low mass e+e- pairs from internal conversion **BNL** CERN SyracuseYale, J. Cobb *et al*, PLB**78** (1978) 519 $\gamma/\pi^0=0.006\pm0.009$ $2<p_T<3$ GeV/c

The first ‘evidence’ for direct-γ was wrong; but internal conversions provided a stringent limit

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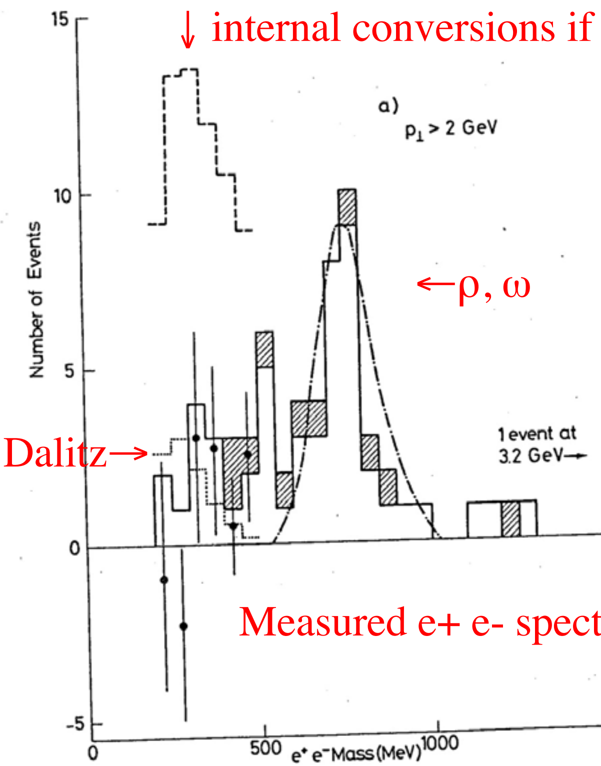
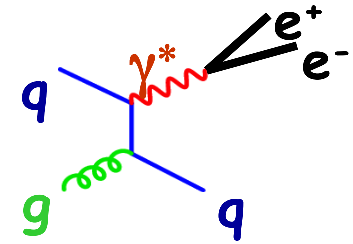


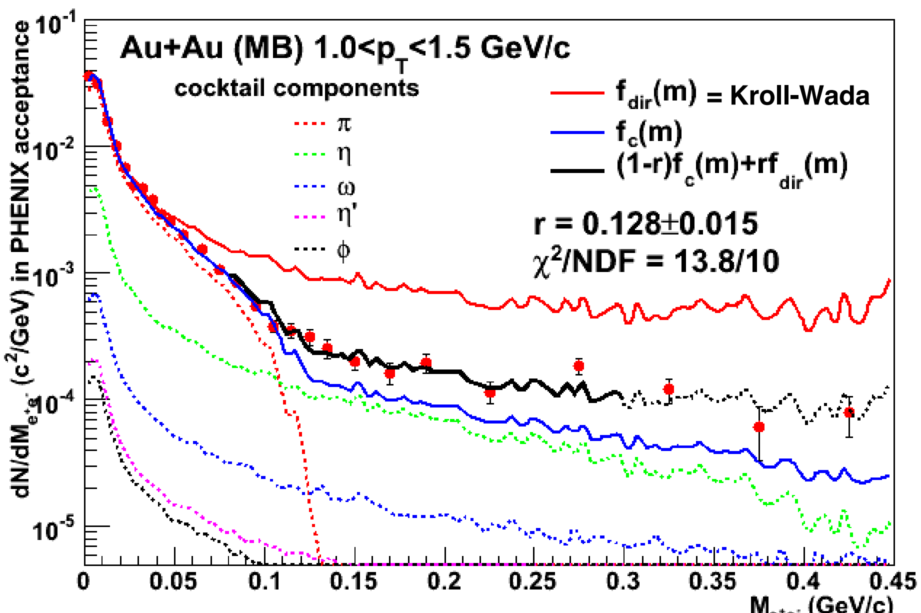
QM2005-direct γ in AuAu via internal conversion

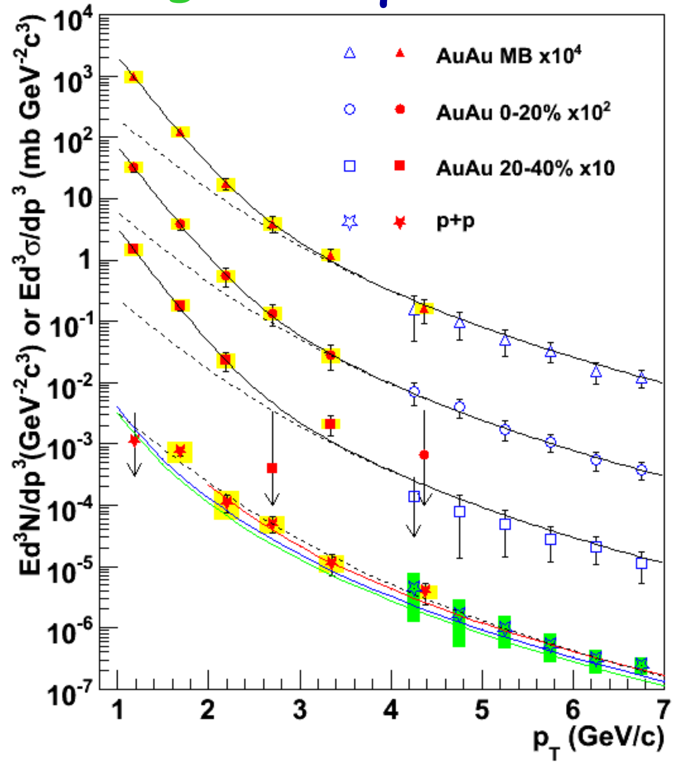
Kroll Wada PR**98**(1955) 1355

PHENIX NPA**774**(2006)403

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\left(1-\frac{m_{ee}^2}{M^2}\right)^3 \mid F(m_{ee}^2)\mid^2 \sqrt{1-\frac{4m_e^2}{m_{ee}^2}}\left(1+\frac{2m_e^2}{m_{ee}^2}\right)$$



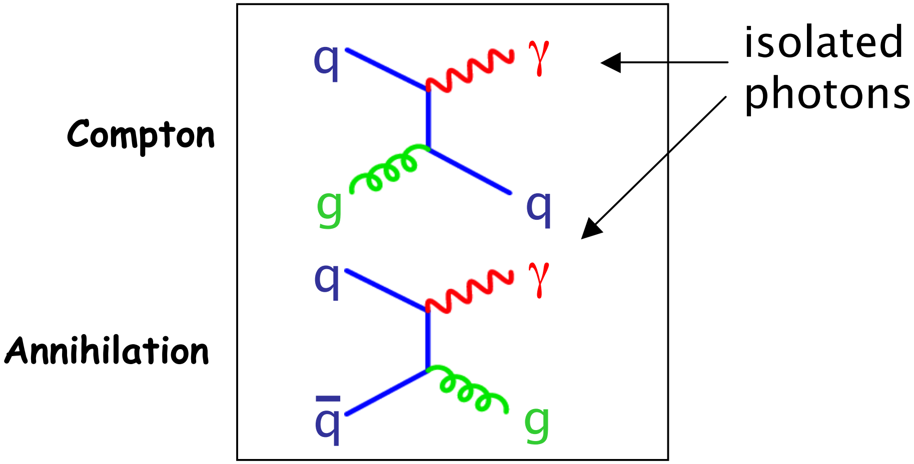


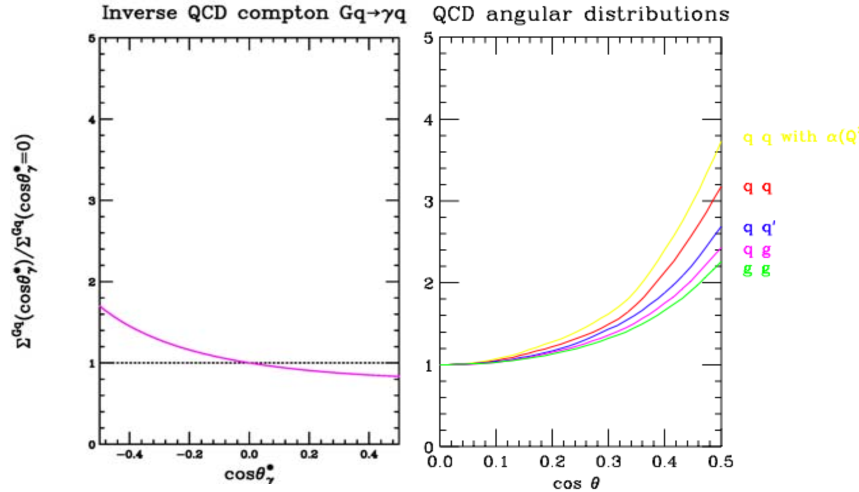


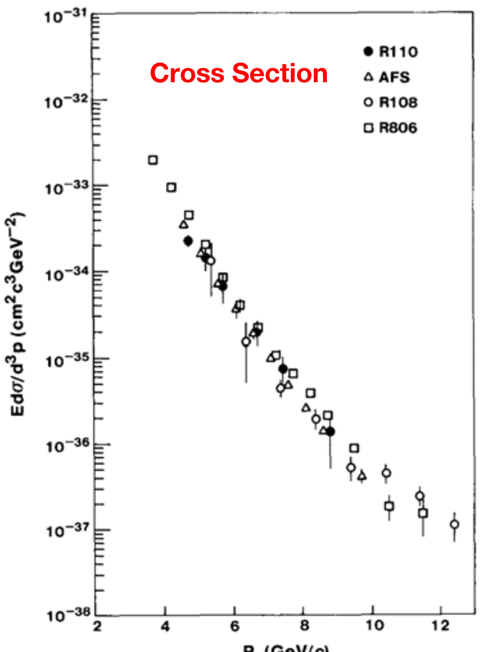
Eliminating the π^0 background by going to $0.2<m_{ee}<0.3$ GeV enables direct γ signal to be measured for $1<p_T<3$ GeV/c in Au+Au. It is exponential, does that mean it is thermal? Yes: the p-p direct γ turns over as $p_T \rightarrow 0$ follows the same function $B(1+p_T^2/b)^{-n}$ used in Drell Yan

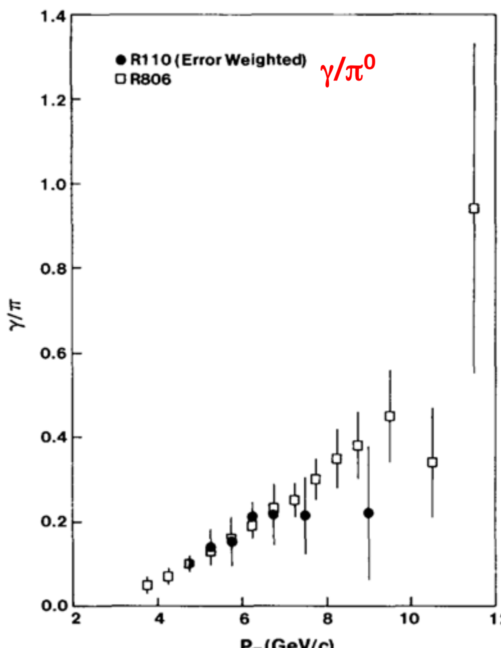
Fit to Au+Au is $[A\, e^{-p_T/T} + \langle T_{AA}\rangle B_{pp}(1+p_T^2/b_{pp})^{-n_{pp}}]$. Significance of exponential (thermal) is > 3 σ. Fitted T=220MeV (is time average)

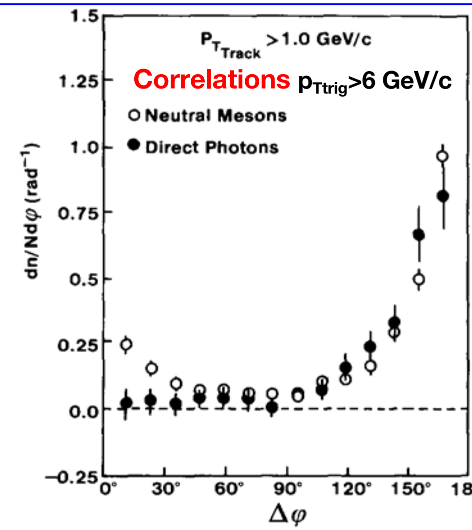
Final ISR direct-γ production + correlations





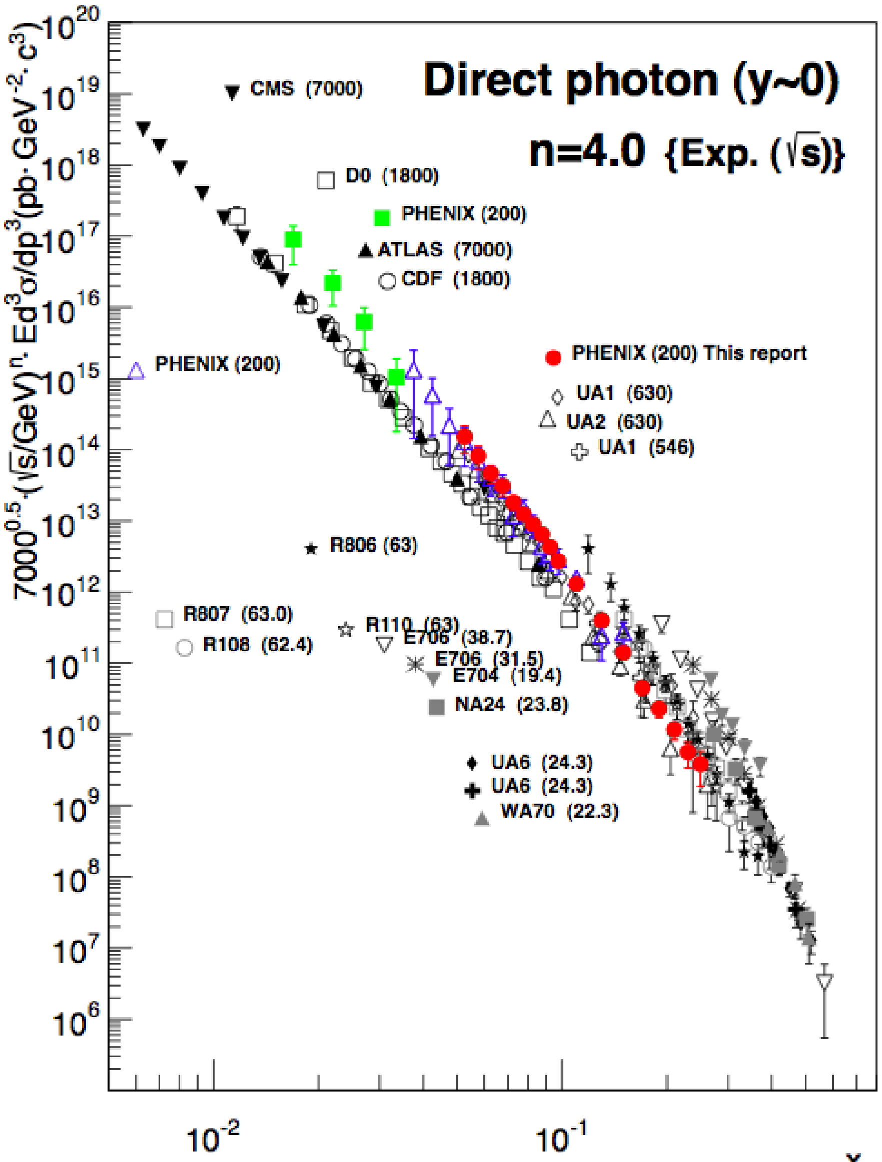






No evidence for bremss. contribution to direct γ--same side correlation is zero--see CMOR NPB**327**, 541 (1989) for full list of references.

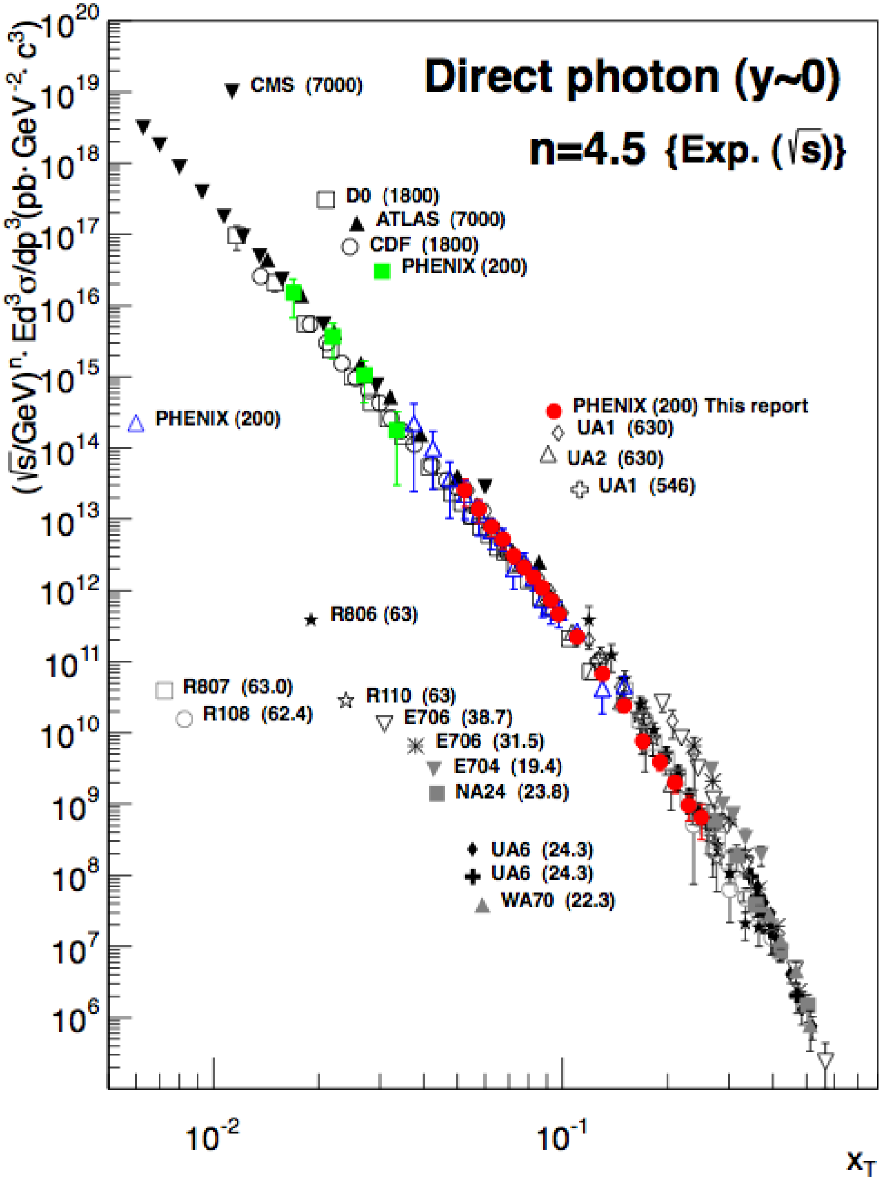
→ QCD in Action 2012



x_T scaling with n_{eff}=4 (parton model) QCD non-scaling is visible

Collection of World's direct-γ measurements (p+p/ p+pbar) including PHENIX low p_T measurement 2 slides back.

→ QCD in Action 2012



x_T scaling with n_{eff}=4.5 works for direct-γ due to QCD non-scaling

Collection of World's direct-γ measurements (p+p/ p+pbar) including PHENIX low p_T measurement 2 slides back.

Back to 1978
Status of ISR single particle measurements

♡ Hard-scattering was visible both at ISR and FNAL (Fixed Target) energies by single particle inclusive at large $p_T \geq$ 2-3 GeV/c.

♡ Scaling and dimensional arguments for plotting data revealed the systematics and underlying physics.

♡ The theorists had the basic underlying physics correct; but many (inconvenient) details remained to be worked out, several by experiment.

♡ k_T, the transverse momentum imbalance of outgoing partons (due to initial state radiation), was discovered by experiment.

k_T is what made $n=4^{++} \rightarrow n=8$

k_T is not a parameter, it can be measured

- In leading order QCD or the Quark-Parton model, the net transverse momentum $\langle p_T \rangle_{\rm pair} = \sqrt{2} \times \langle k_T \rangle$, of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high p_T photons, or the $\gamma+$ Jet pair for direct photon production is zero. All the above pairs should be coplanar with the incident beam axis.
- However, early Drell-Yan and inclusive high p_T particle studies showed that k_T was measurable and non-zero.

♡ The history of k_T is worth reviewing as k_T was predicted to be zero by theorists, but was discovered to be non-zero by experimentalists. The CCHK experiment [M. Della Negra, et al., Nucl. Phys. **B127**, 1 (1977)] discovered that back-to-back jets had considerable out of plane transverse momentum $p_{\rm out}$, and proposed that this was due to transverse momentum of partons inside a proton.

Feynman Field & Fox to the rescue

♡ This was elaborated by Feynman, Field and Fox, [Nucl. Phys. **B128**, 1, (1997), Phys Rev. **D18**, 3320 (1978)] who introduced the k_T phenomenology of a parton in a proton, which they discussed in terms of 'intrinsic transverse momentum' from confinement which would be constant as a function of x and Q^2, and NLO effects due to hard gluon emission which would vary with x and Q^2, but they used an constant 'effective' k_T to 'explain' the available measurements.

♡ A subsequent ISR experiment, CCOR, showed that k_T for jet-pairs was roughly the same as for Drell-Yan and increased similarly with $\sqrt{s}$ (and p_T) i.e. was not constant.

k_T and NLO are distinct---e.g. Drell Yan

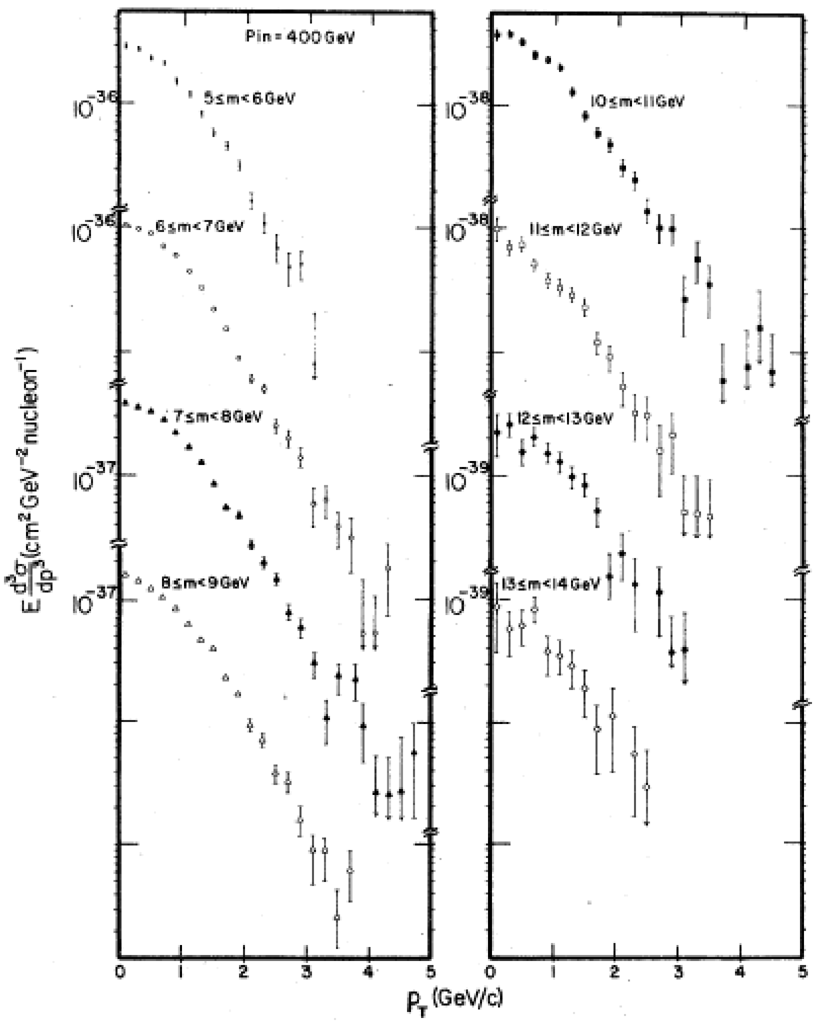
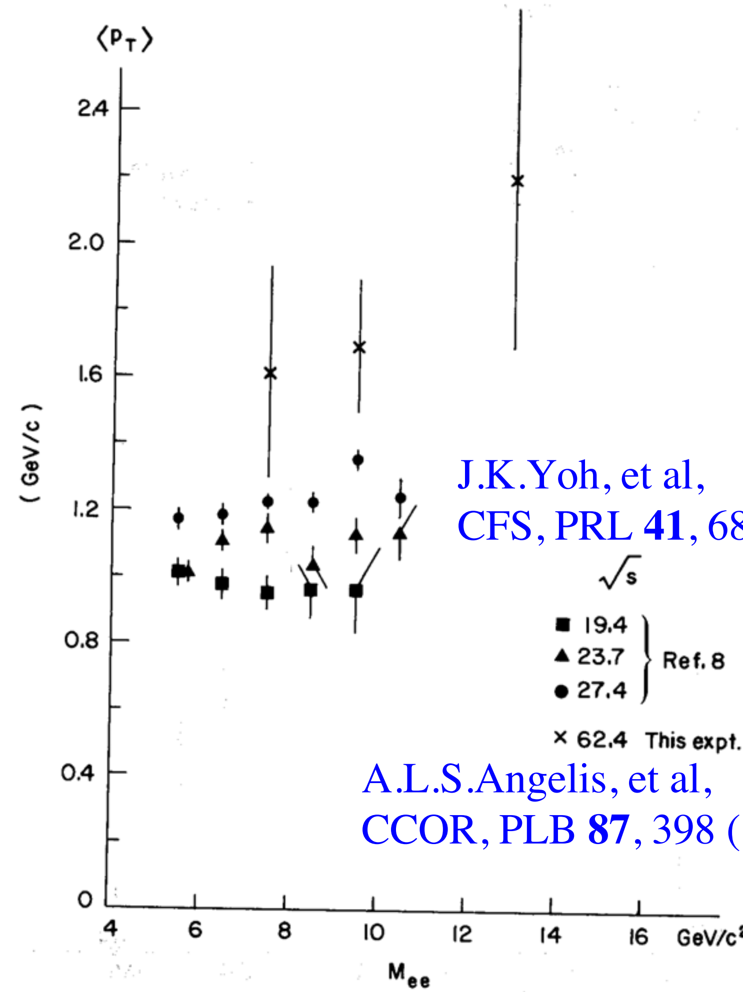


FIG. 12. Invariant yield of dimuons as a function of the transverse momentum p_T of the muon pair for 400 GeV incident protons.

A.S.Ito, et al, PRD23,604 (1981)



J.K.Yoh, et al,
CFS, PRL **41**, 684 (1978)

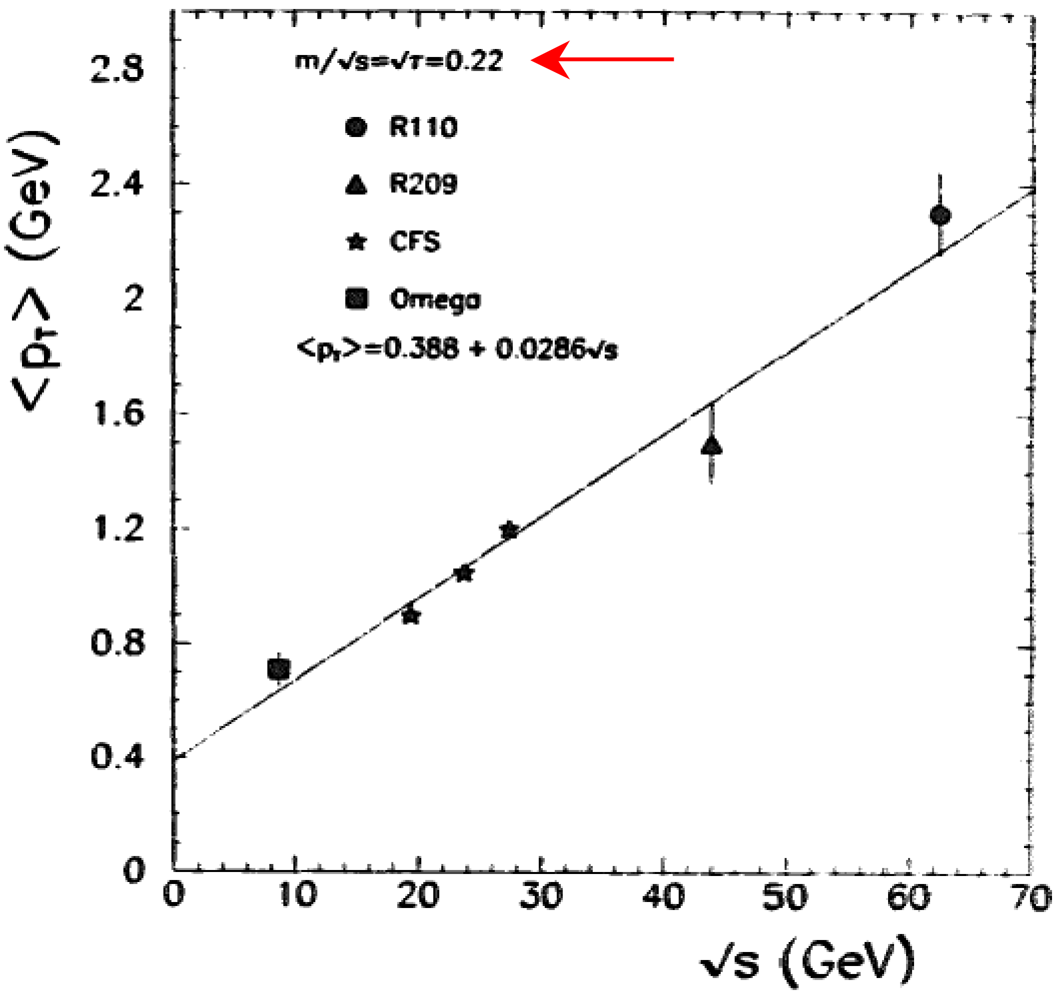
A.L.S.Angelis, et al,
CCOR, PLB **87**, 398 (1979)

Note Gaussian shape, no power-law tail!

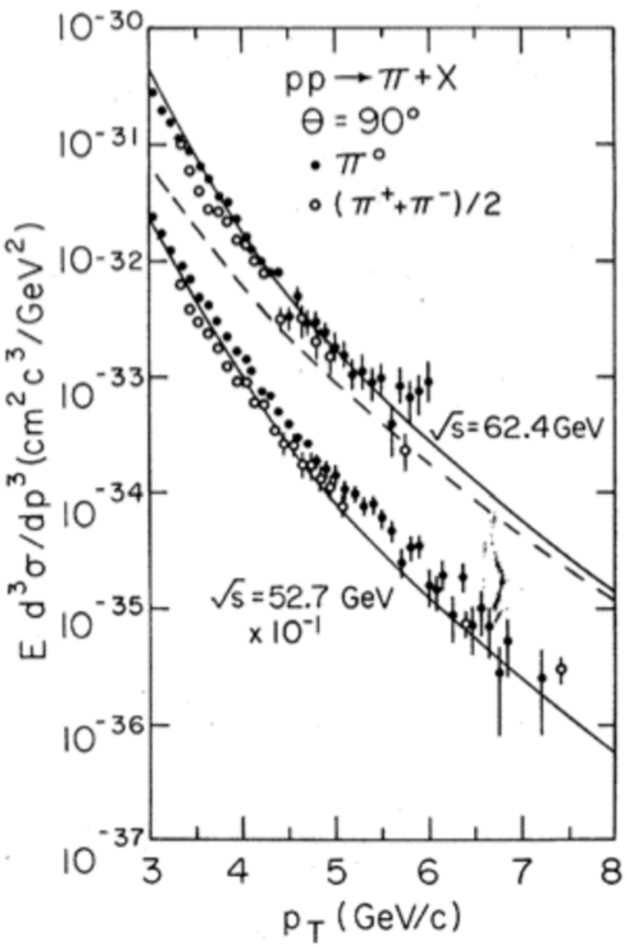
$\langle p_T \rangle (=\sqrt{2}k_T)$ vs $\sqrt{s}$ in Drell-Yan

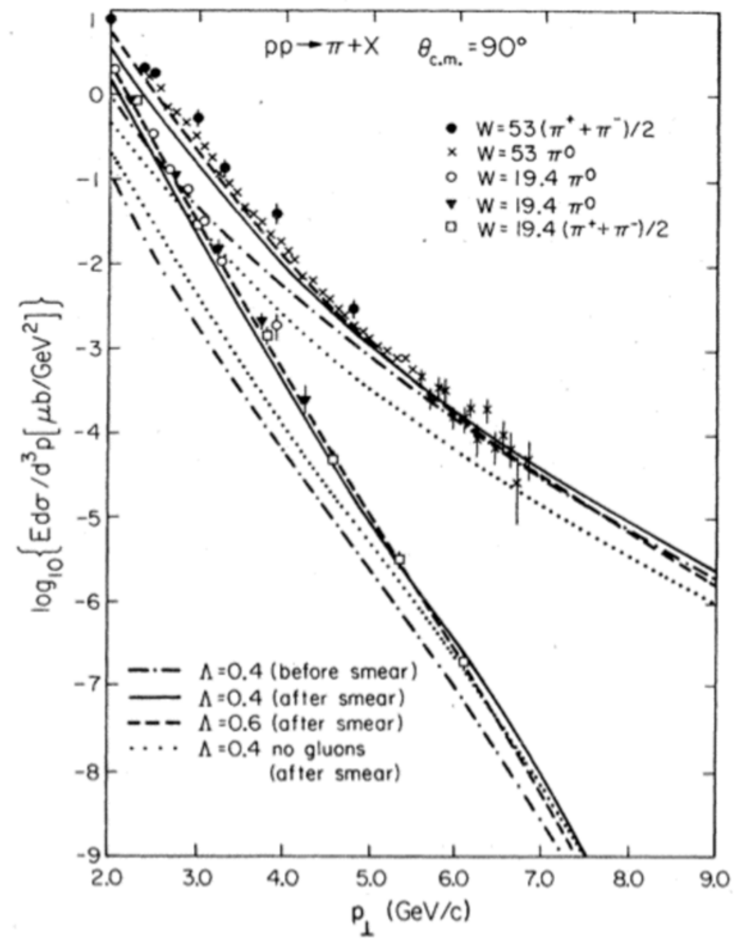
A.L.S. Angelis et al. / Massive electron pairs

CMOR, NPB348, 1 (1991)



Owens and FFF QCD calculations inclusive π^0





Owens, Kimel PRD**18**(1978)3313

Feynman,Field,Fox, PRD**18**(1978)3320

Note that k_T smearing dramatically improves agreement at lower p_T

Status of QCD Theory in 1978

- The first modern QCD calculation and prediction for high p_T single particle inclusive cross sections including non-scaling and initial state radiation was done in 1978 by J. F. Owens, E. Reya, M.Gluck, PRD **18**, 1501 (1978), "*Detailed quantum-chromodynamic predictions for high-p_T processes*," and J.F. Owens, J. D. Kimel, PRD **18**, 3313 (1978), "*Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes*".

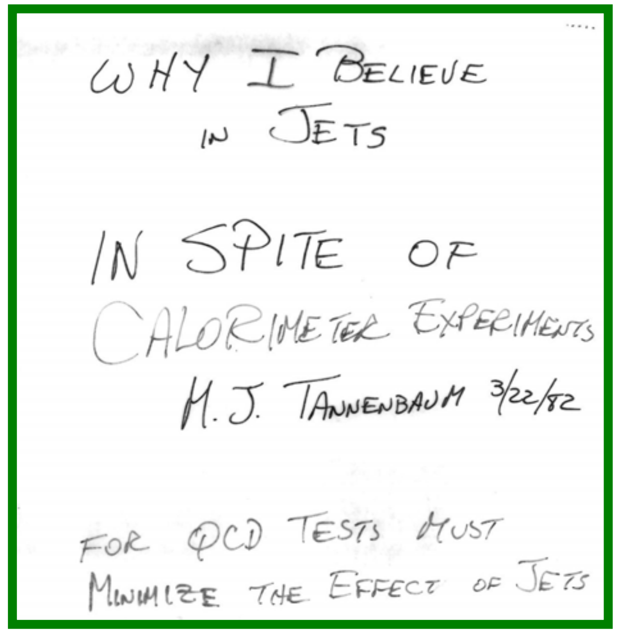
- This work was closely followed and corroborated by Feynman, Field, Fox PRD **18**, 3320 (1978), "*Quantum-chromodynamic approach for the large-transverse-momentum production of particles and jets*."

- Unfortunately jets in 4π Calorimeters at ISR energies or lower are invisible below $\sqrt{\hat{s}} \simeq E_T \leq 25$ GeV, which led to considerable confusion in the period 1980-1982.

QCD and Jets are now a cornerstone of the standard model

- Incredibly at the famous Snowmass conference in July 1982, many if not most people in the U.S. were skeptical

e.g. MJT Seminar in 1982


WHY I BELIEVE IN JETS

IN SPITE OF CALORIMETER EXPERIMENTS

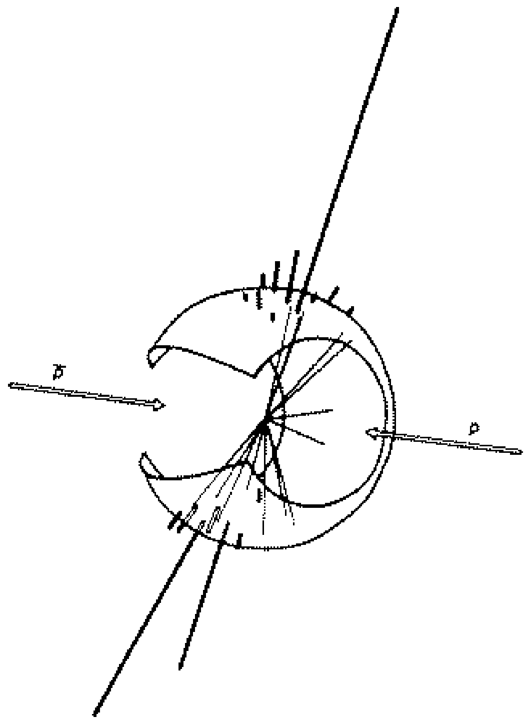
M. J. TANNENBAUM 3/22/82

FOR QCD TESTS MUST MINIMIZE THE EFFECT OF JETS

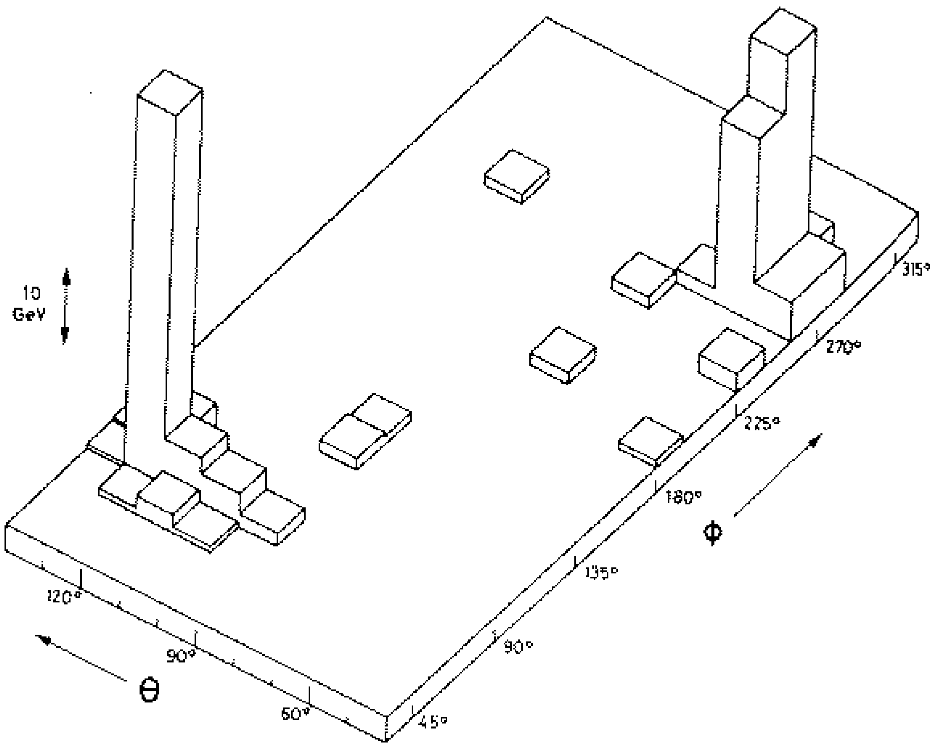
- The International HEP conference in Paris, three weeks later, July 26--31, 1982 changed everything.

Paris 1982-THE UA2 Jet

From 1980--1982 most high energy physicists doubted jets existed because of the famous NA5 E_T spectrum which showed NO JETS. This one event from UA2 in 1982 changed everybody's opinion.



(a)



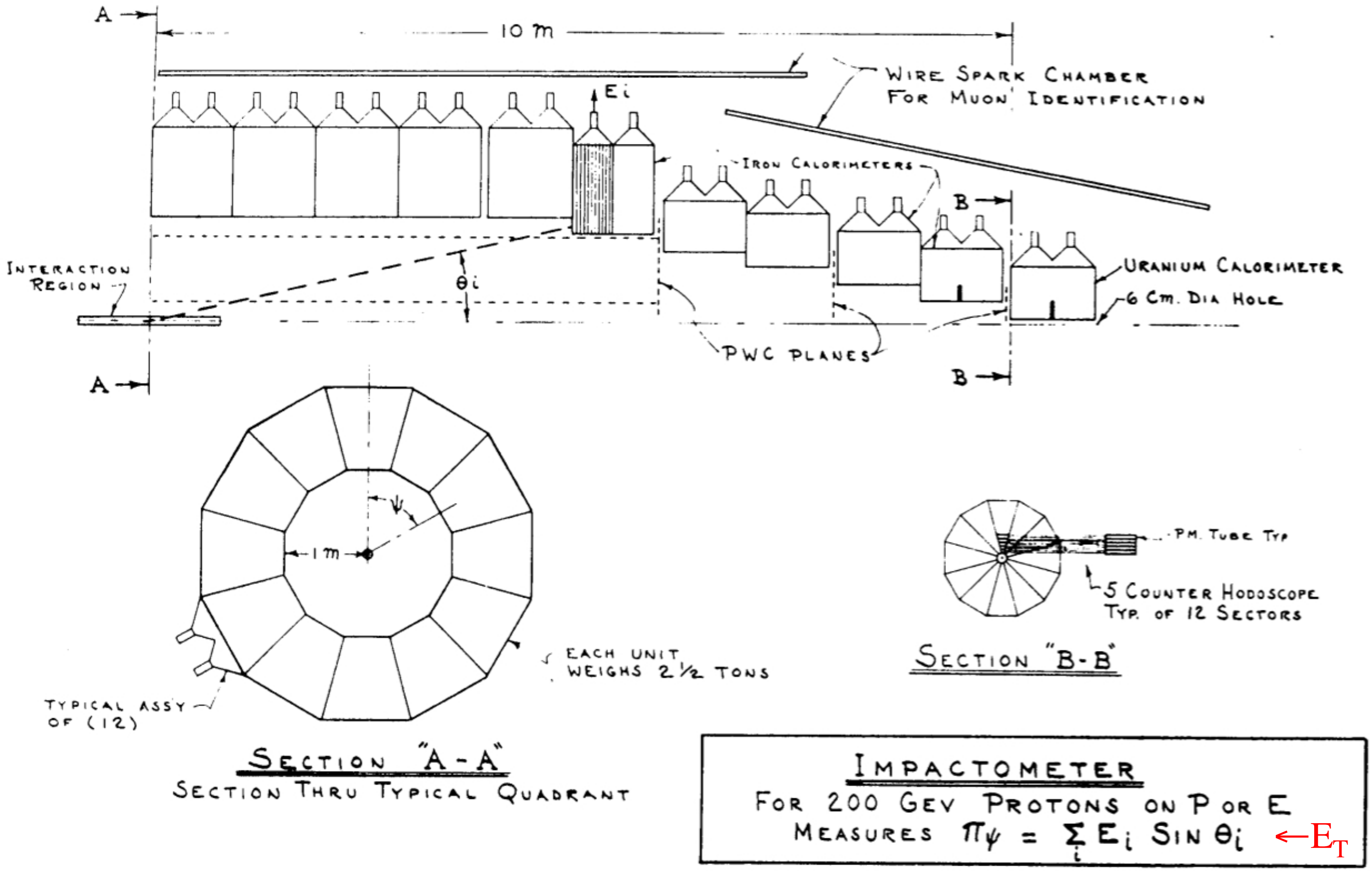
(b)

Why nobody (in the U.S.) believed in jets

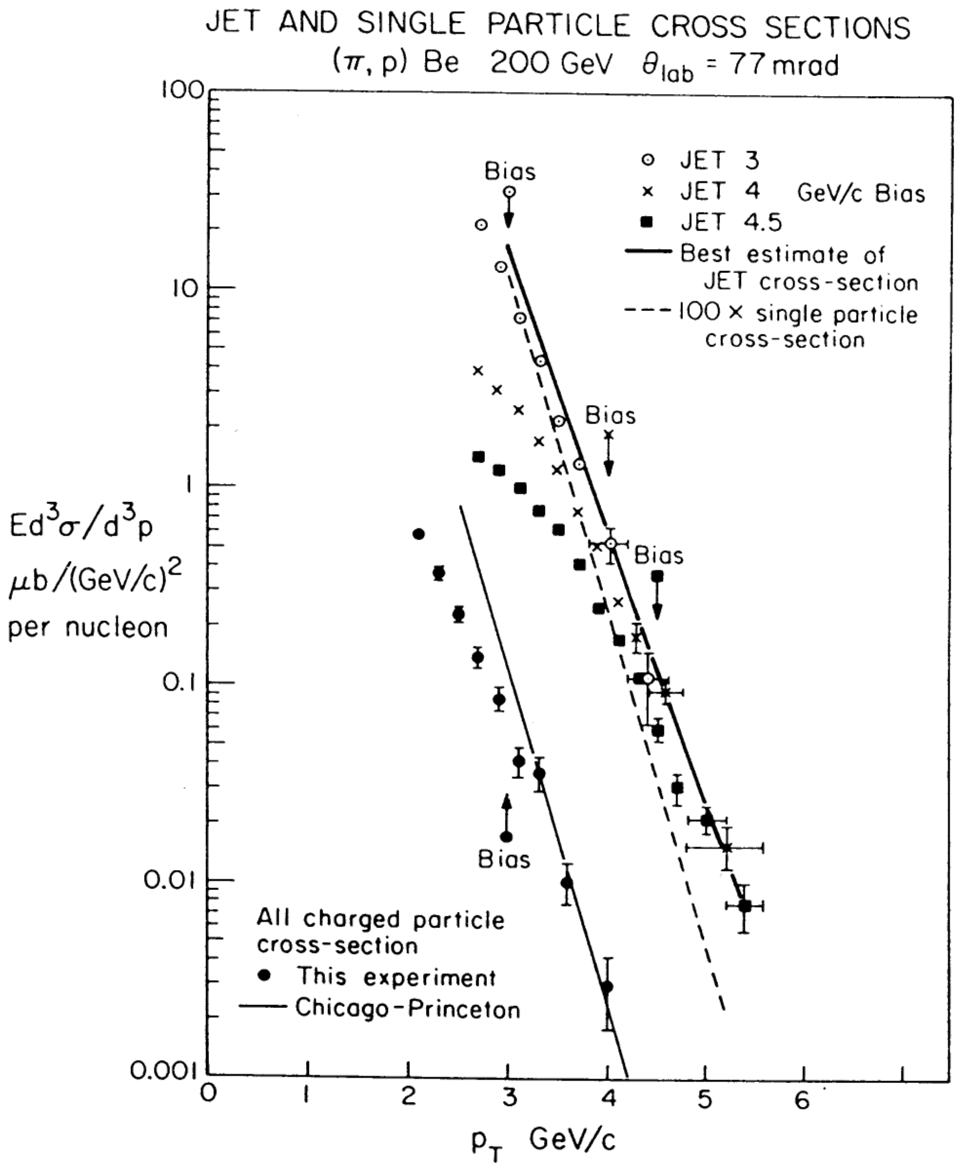
- In 1972-73, soon after hard-scattering was discovered in p-p collisions, Bjorken PRD**8** (1973) 4098 and Willis (ISABELLE Physics Prospects-BNL-17522) proposed 4π hadron calorimeters to search for jets from fragmentation of scattered partons with large p_T realizing that a substantial increase in rate would be expected in measuring the entire jet at a given p_T rather than just the leading fragment. (Bjorken's parent-child effect)
- It took until 1980 to get a full azimuth $\Delta\eta \sim \pm 0.88$ ($\Delta\Theta \sim \pm 45^o$) calorimeter but meanwhile experiments were done with smaller back-to-back calorimeters each with aperture $\Delta\Phi \sim \pm 45^o$ $\Delta\eta \sim \pm 0.55$ and many new trigger biases were discovered, for instance, jets wider than the calorimeter aperture would deposit less energy than narrow jets of the same p_T and be suppressed by the steeply falling spectrum $\Rightarrow$ jet structure is dominated by the calorimeter geometry [e.g. see M. Dris NIM **158** (1979) 89]

Willis ‘impactometer’ from Isabelle Study 1972

4π hadron calorimeter non-magnetic detector. Sound familiar?



(In)famous FNAL E260 found "Jets" (1977)

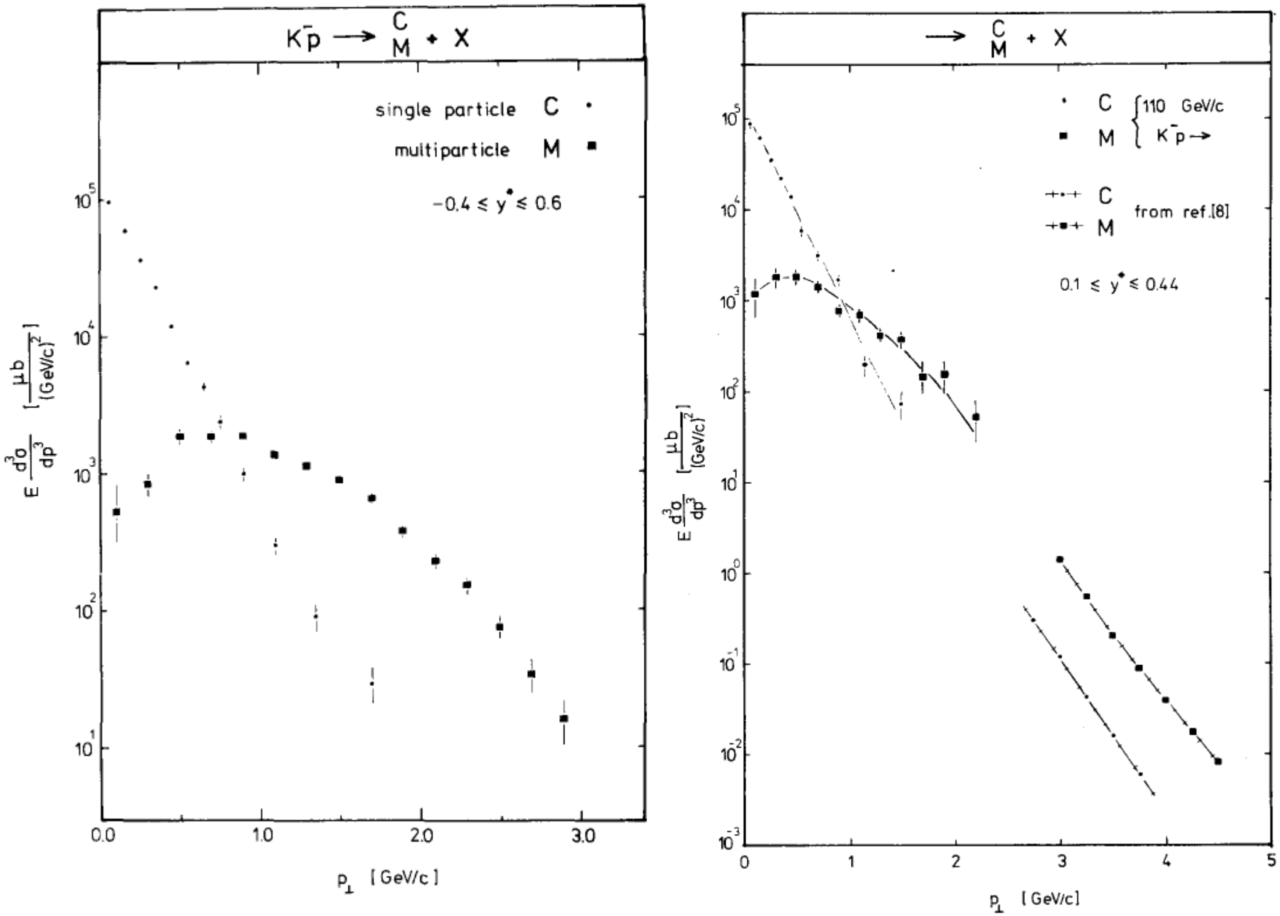


- In each of 2 back to back calorimeters with $\Delta\Phi \sim \pm 45^{o}$ $\Delta\eta \sim \pm 0.36$ (same as PHENIX) the invariant cross section of several particles with a vector sum p_T is much larger than a single particle of the same p_T. The authors took this as evidence for the exactly back-to-back in azimuth jets of constituent scattering⇒Never let an interested theorist collaborate on an experiment.

C.Bromberg et al E260, PRL 38 (1977)1447, NPB134 (1978) 189

But, experiments with different apertures got different results

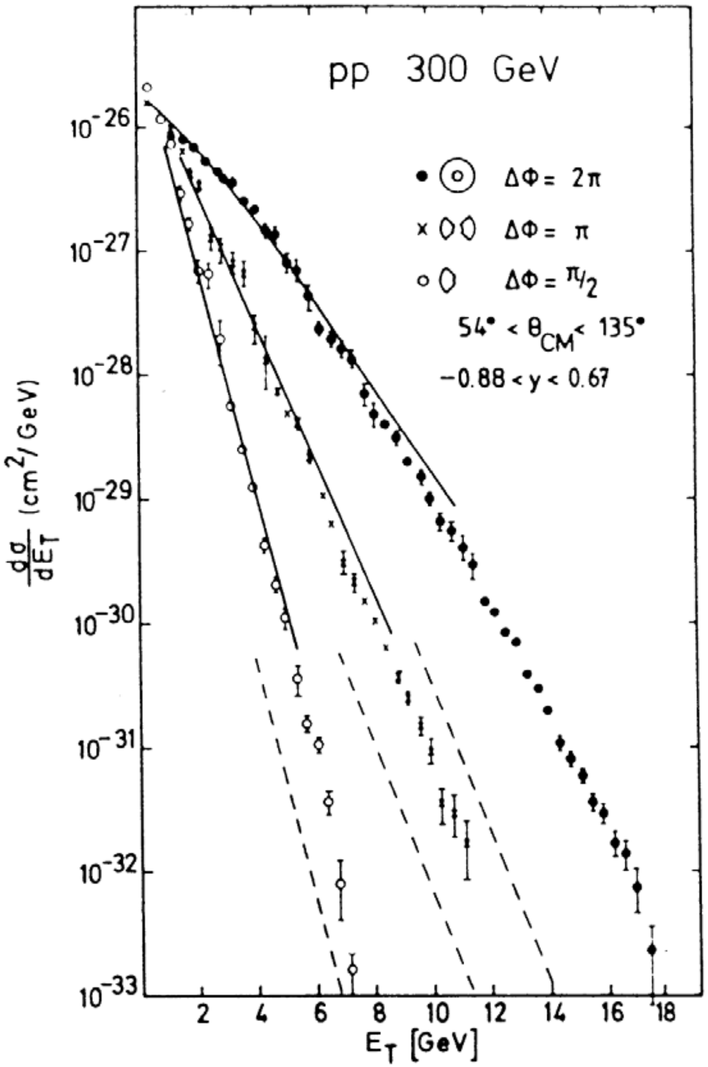
- The first 4π experiment was a bubble chamber(!) 110 GeV/c K^- on p [M. Deutschmann, et al, ABCCLVW collab, NPB**155** (1979)307]



- multiparticle cross section for p_T> 1.5 GeV/c >> single particle
- Data extrapolate nicely to those of E260 [8] in slope and magnitude.
- But ``principal axis" analysis of the data shows "the vast majority of events with large p_T multiparticle systems DO NOT exhibit jet-like structure."

NA5-the coup-de-grâce to jets (1980)

- Full azimuth calorimeter $-0.88<\eta^*<0.67$ ($\rightarrow$ NA35, NA49)



- plus triggered in two smaller apertures corresponding to E260.
- No jets in full azimuth data
- All data way above QCD predictions--------
- The large E_T observed is the result of "a large number of particles with a rather small transverse momentum"--the first E_T measurement in the present terminology.

K. Pretzl, Proc 20th ICHEP (1980)
C. DeMarzo et al NA5, PLB**112**(1982)173

For more on E_T see MJT IJMPA **4** (1989)3377

Back to Paris 1982-THE UA2 Jet

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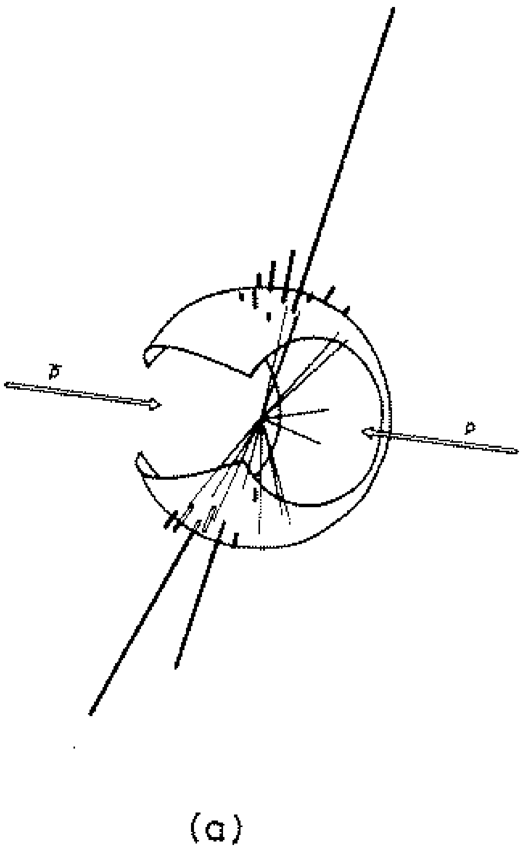
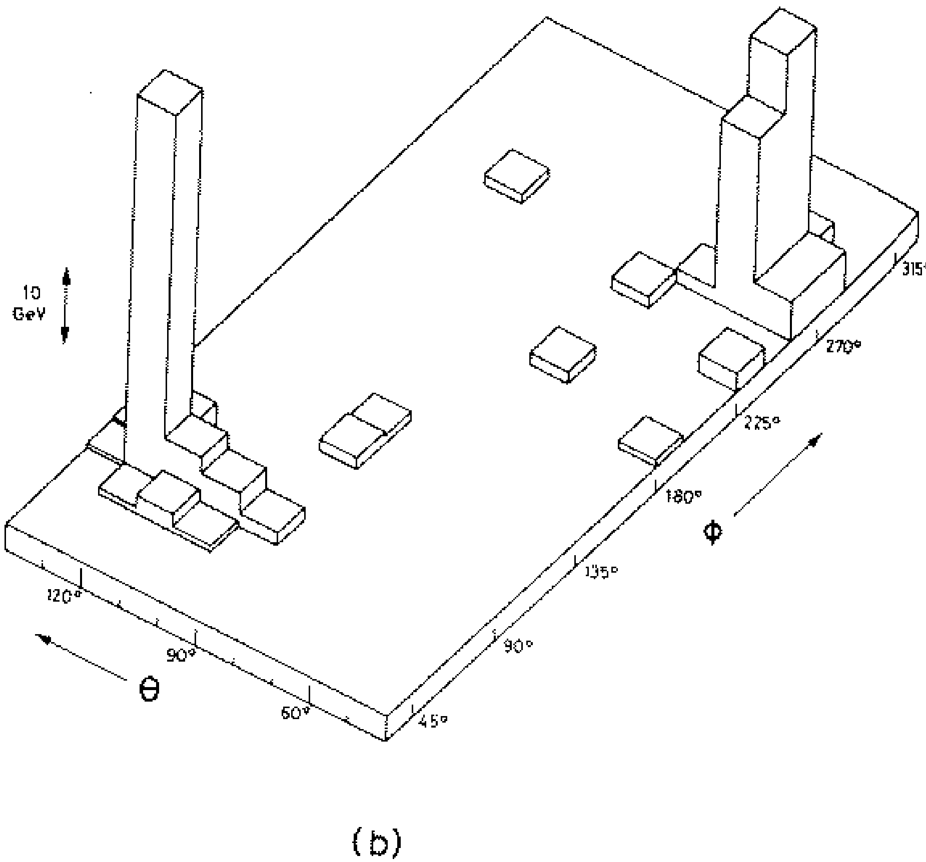
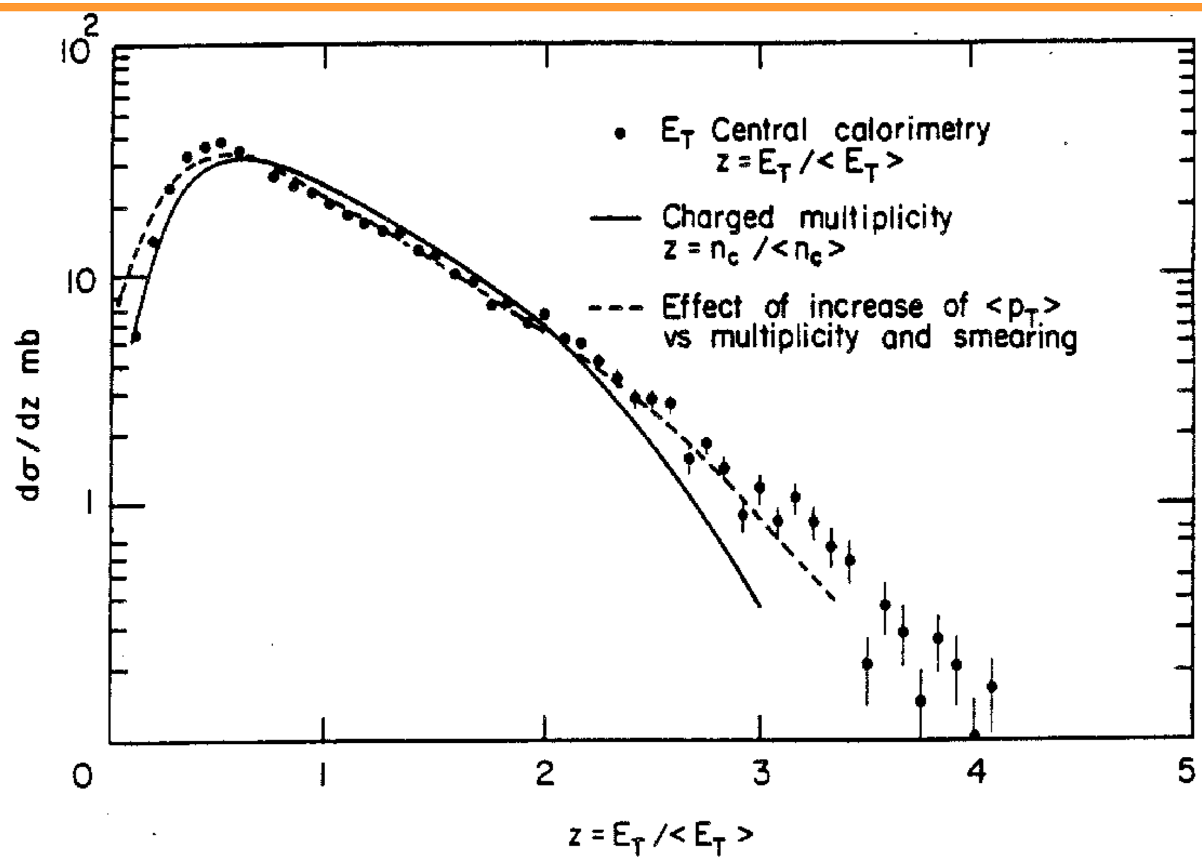
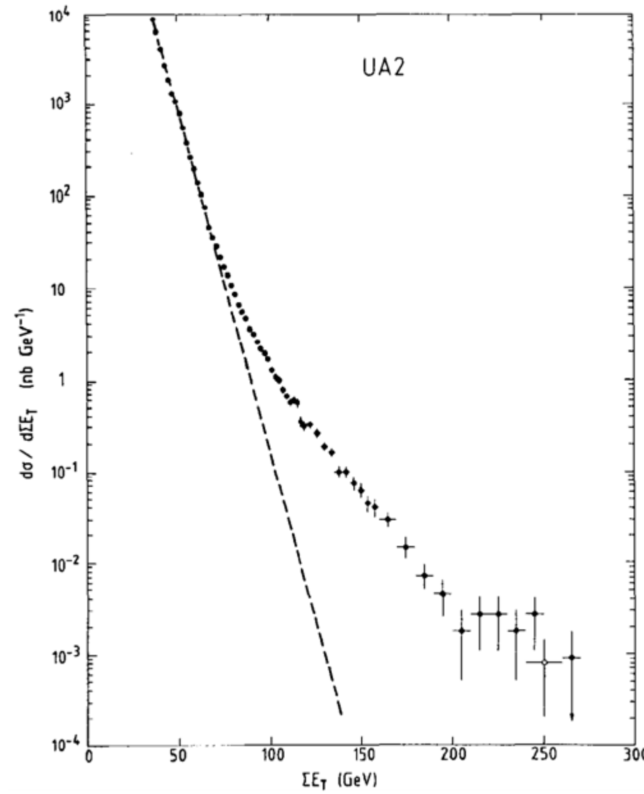




UA1-Carlo himself explained E_T (no jet) dist. before seeing UA2 plot. Explanation is correct



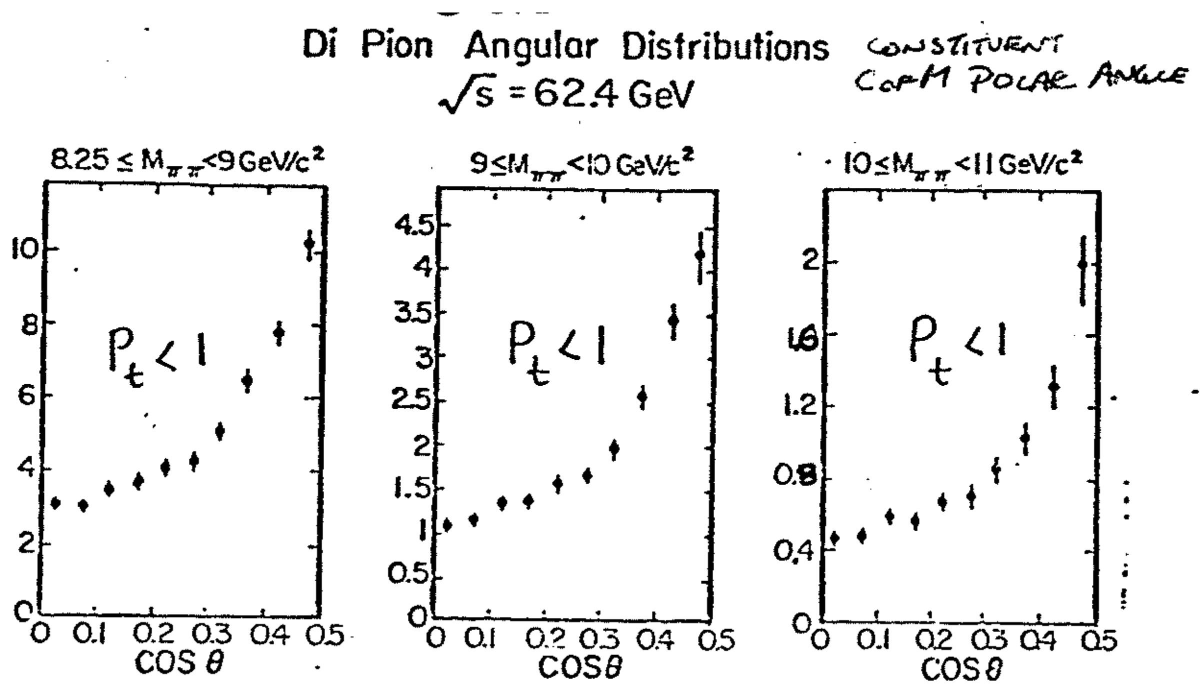


UA1 (1982) Paris-withdrawn (C.Rubbia) $\sqrt{s}$=540 GeV. No Jets because E_T is like multiplicity (n), composed of many soft particles near $<p_T>$! CERN-EP-82/122.

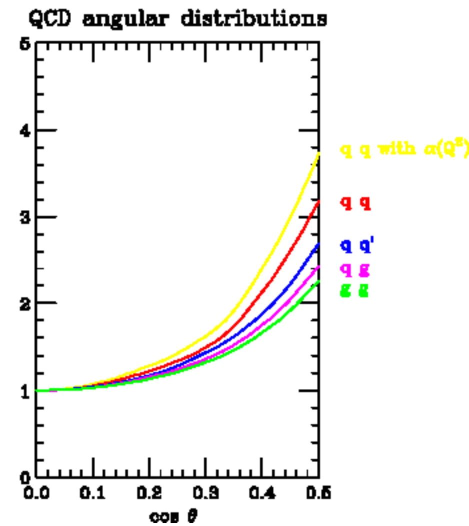
OOPS UA2 discovers jets ~5-6 orders of magnitude down in E_T distribution!

Also Paris1982-first measurement of QCD subprocess angular distribution using π^0-π^0 correlations

DATA: CCOR NPB 209, 284 (1982)



QCD



$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

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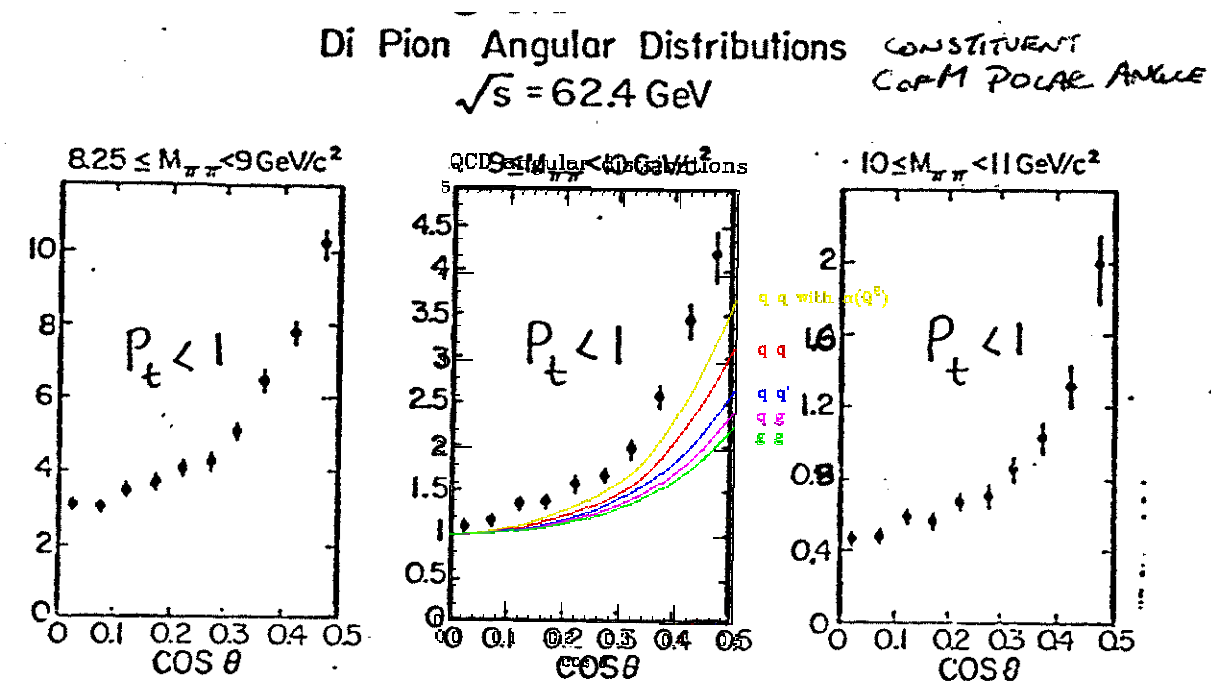
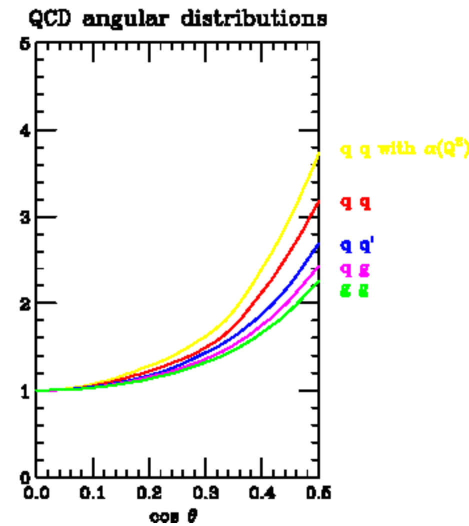


QCD



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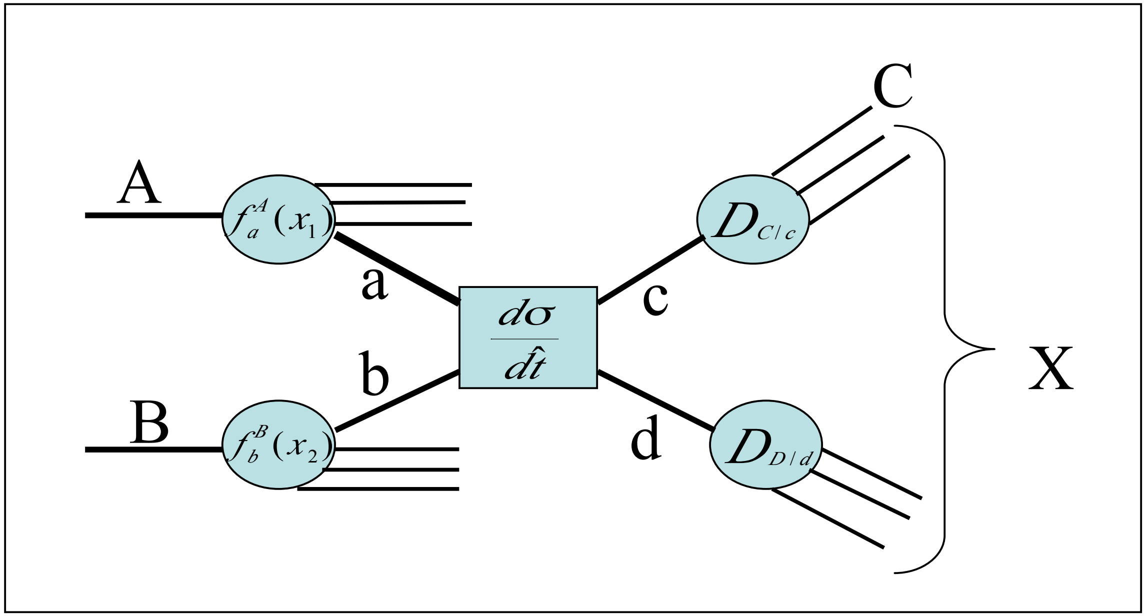
LO-QCD in 1 slide



LO-QCD in 1 slide

Cross Section in p-p collisions c.m. energy $\sqrt{s}$

The overall p-p reaction cross section
is the sum over constituent reactions

$$a + b \to c + d$$

$f_a^A(x_1)$, $f_b^B(x_2)$, are structure functions, the differential probabilities
for constituents a and b to carry momentum fractions x_1 and x_2
of their respective protons, e.g. $u(x_1)$,

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s} \sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2} \Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions
and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

Σ^{ab} (cosθ*) in LO-QCD

a) $qq' \to qq'$, $\bar{q}q' \to \bar{q}q'$ $\quad \dfrac{4}{9}\dfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$

b) $qq \to qq$ $\quad \dfrac{4}{9}\left(\dfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\dfrac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\dfrac{8}{27}\dfrac{\hat{s}^2}{\hat{u}\hat{t}}$

c) $\bar{q}q \to \bar{q}'q'$ $\quad \dfrac{4}{9}\dfrac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$

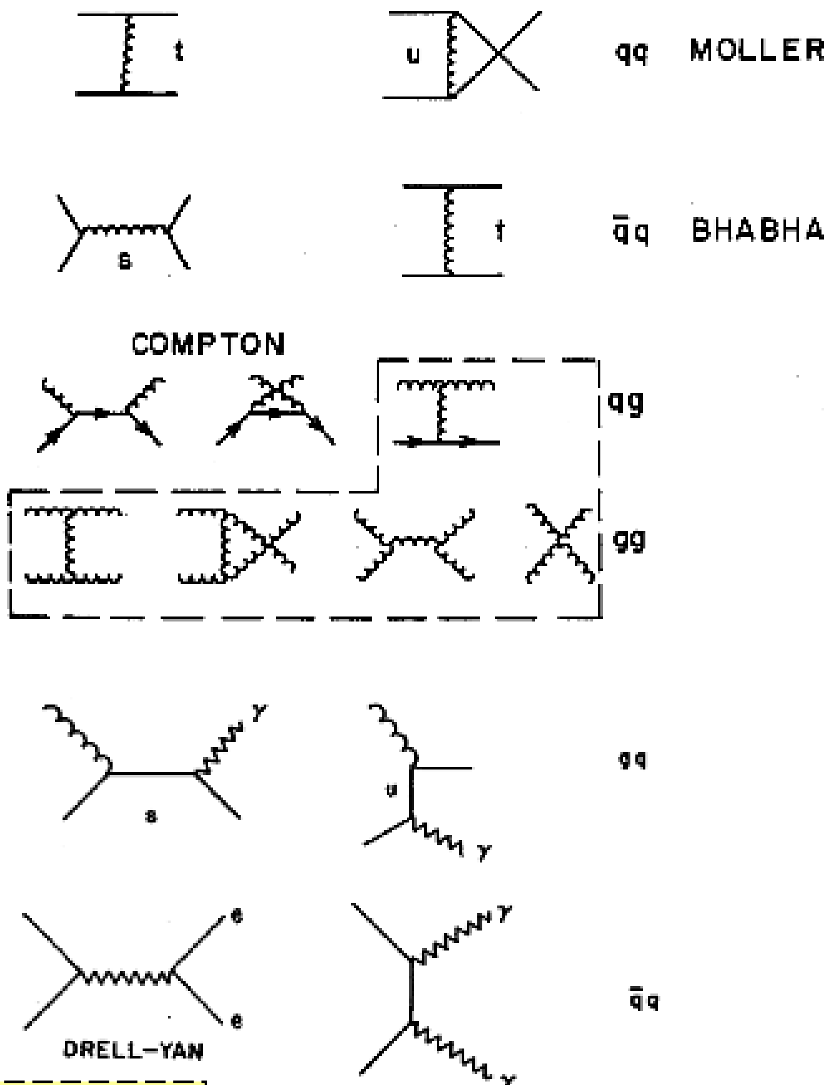
d) $\bar{q}q \to \bar{q}q$ $\quad \dfrac{4}{9}\left(\dfrac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\dfrac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\dfrac{8}{27}\dfrac{\hat{u}^2}{\hat{s}\hat{t}}$

e) $\bar{q}q \to gg$ $\quad \dfrac{32}{27}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\dfrac{8}{3}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$

f) $gg \to \bar{q}q$ $\quad \dfrac{1}{6}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}-\dfrac{3}{8}\dfrac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}$

g) $qg \to qg$ $\quad -\dfrac{4}{9}\dfrac{\hat{u}^2+\hat{s}^2}{\hat{u}\hat{s}}+\dfrac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}$

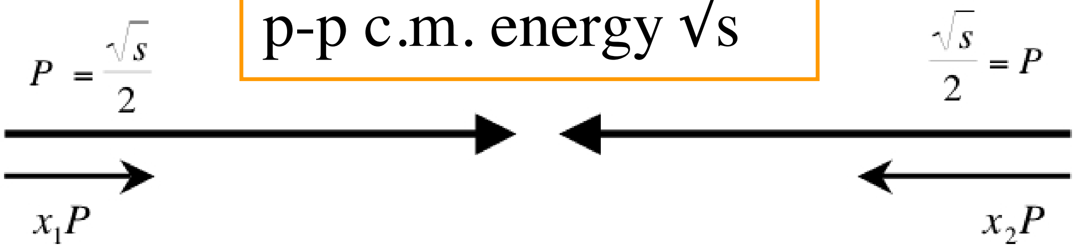
h) $gg \to gg$ $\quad \dfrac{9}{2}\left(3-\dfrac{\hat{u}\hat{t}}{\hat{s}^2}-\dfrac{\hat{u}\hat{s}}{\hat{t}^2}-\dfrac{\hat{s}\hat{t}}{\hat{u}^2}\right)$



QCD is like QED except for the gluon self coupling

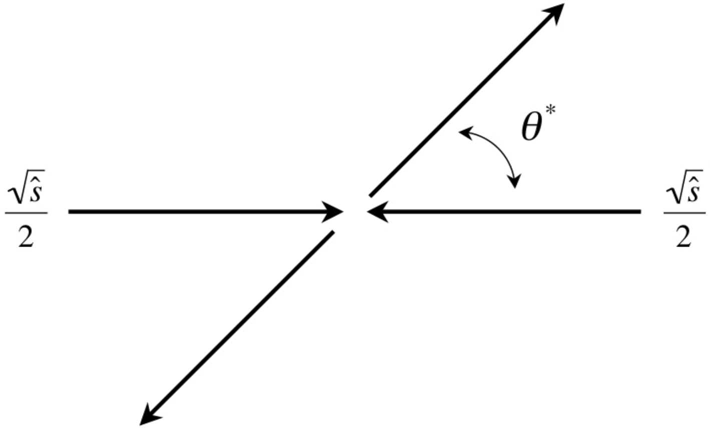
Constituent Kinematics

p-p c.m. energy √s



In p-p c.m. system, parton-parton c.m. energy

$$\hat{s} = x_1 x_2 s$$



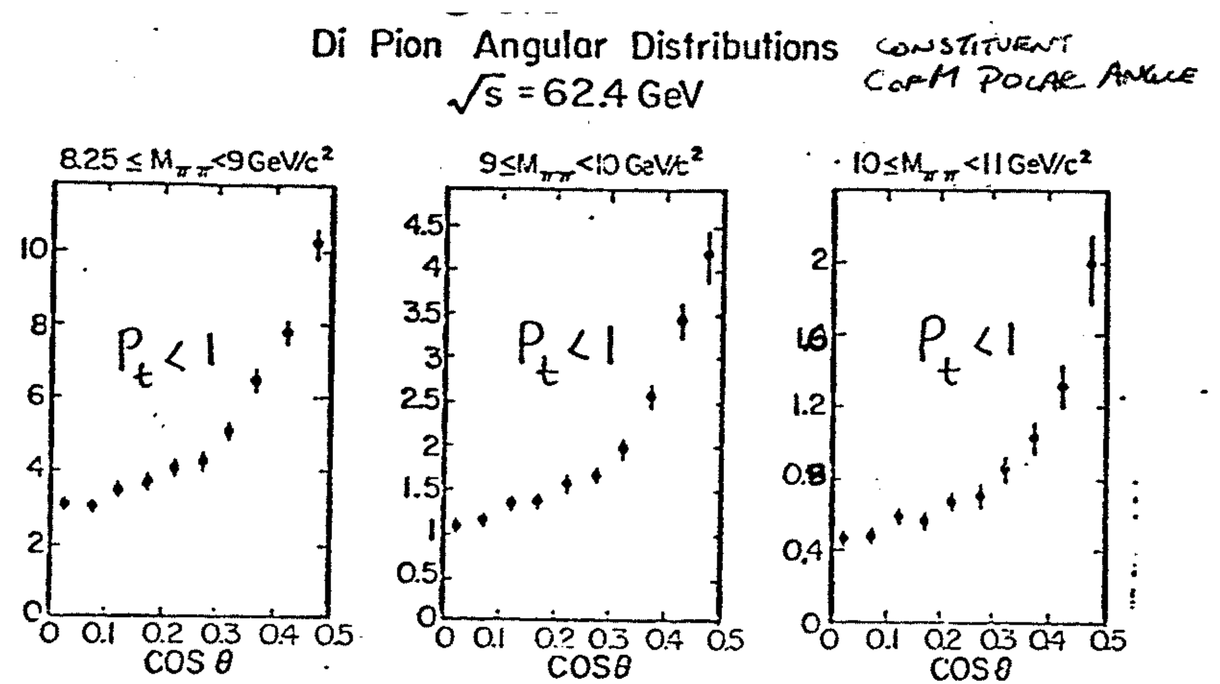
In parton-parton c.m. system scattering angle is θ*

$$\boxed{Q^2 = -\hat{t} = \hat{s}\frac{(1-\cos\theta^*)}{2}}$$

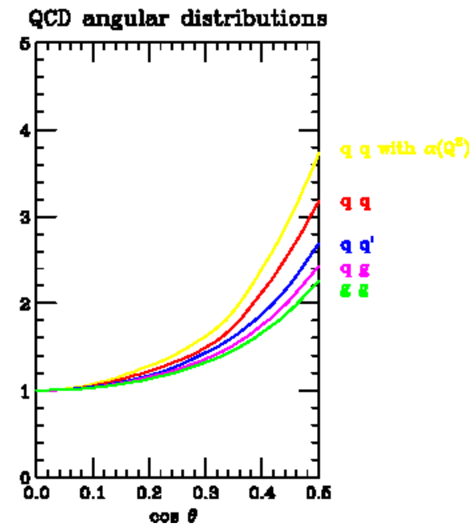
$$\boxed{-\hat{u} = \hat{s}\frac{(1+\cos\theta^*)}{2}}$$

Back to Paris1982-first measurement of QCD subprocess angular distribution using π^0-π^0 correlations: need $\alpha_s(Q^2 \hat{=} \hat{t})$

DATA: CCOR NPB 209, 284 (1982)



QCD



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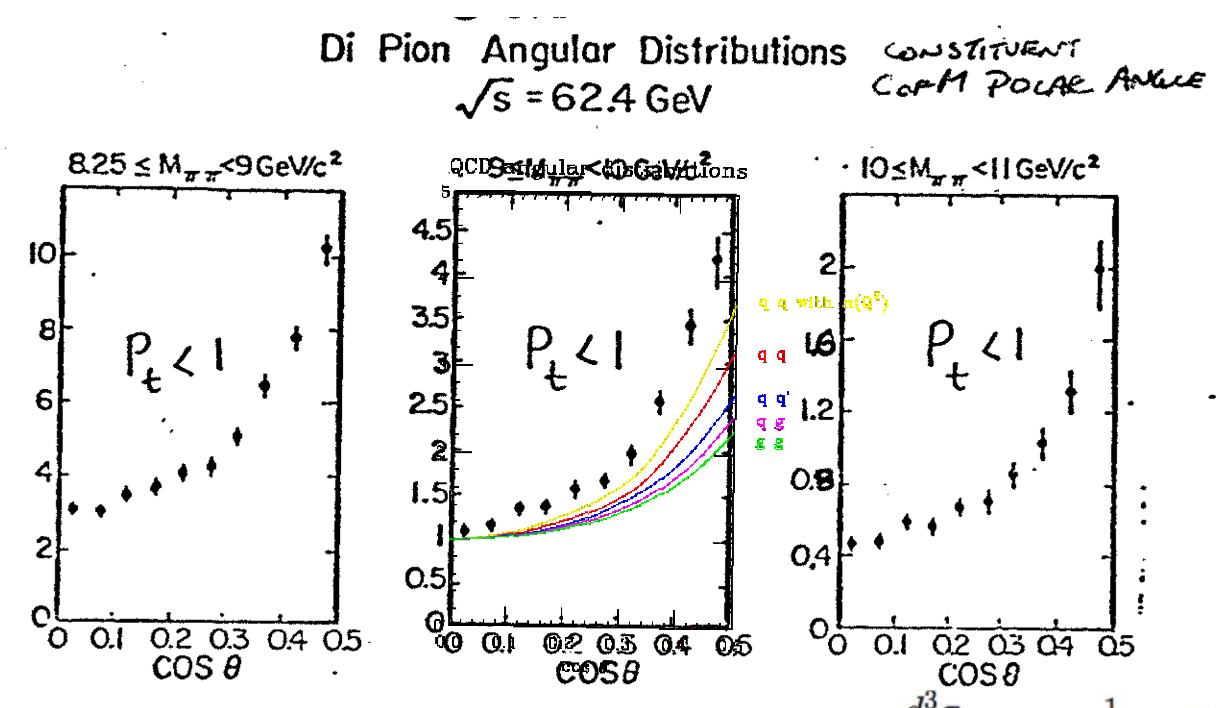
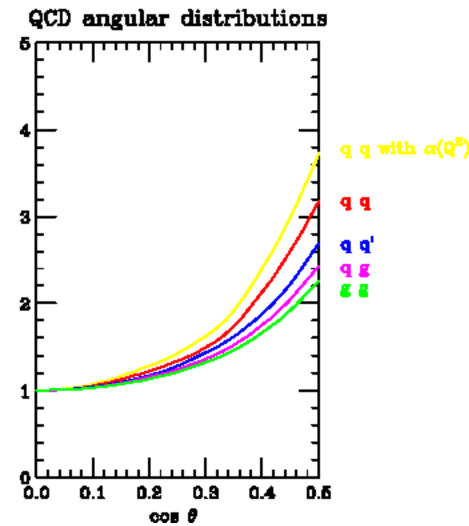


QCD



$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25\ln(Q^2/\Lambda^2)}$ are predicted by QCD

Eventually this was measured with di-jets

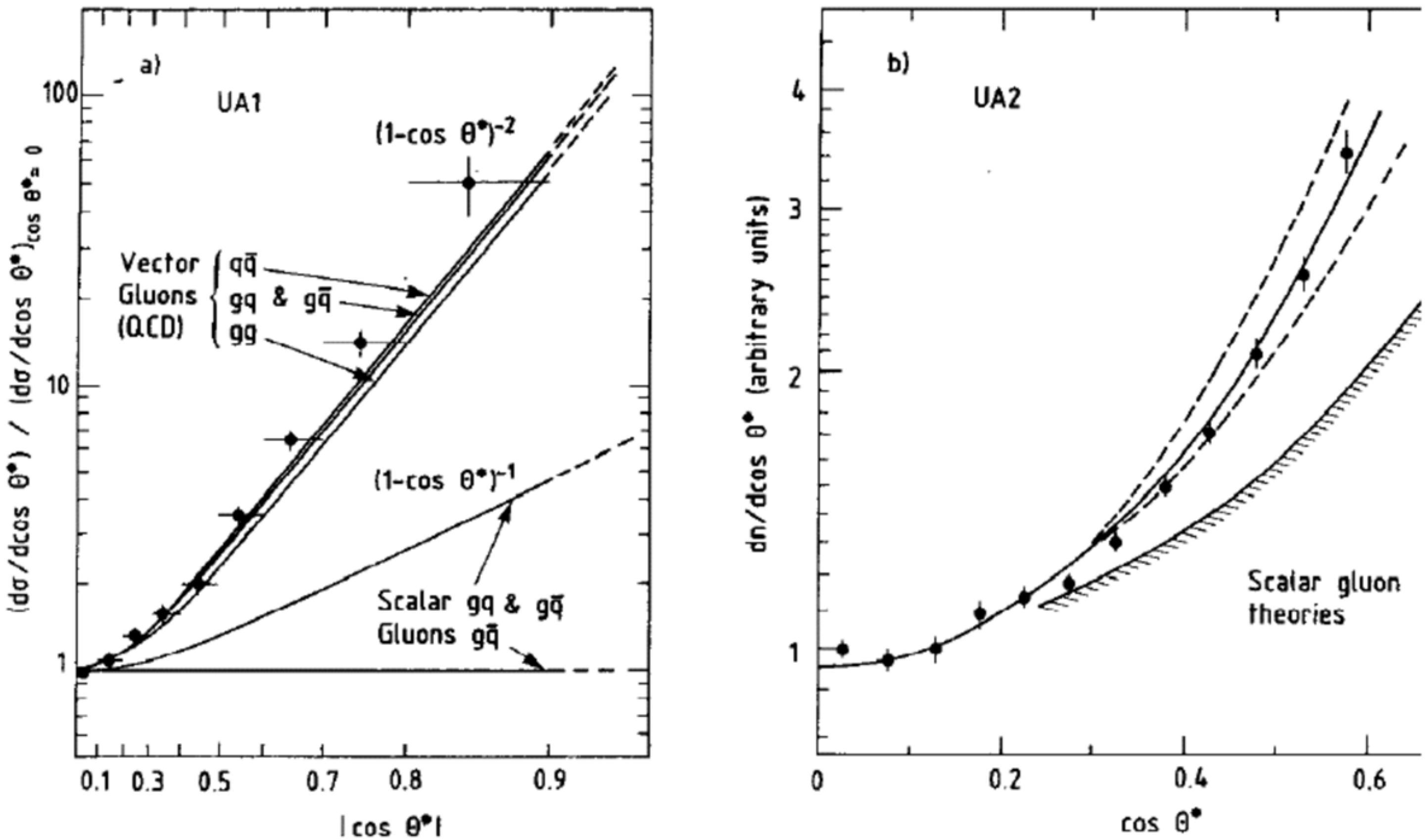
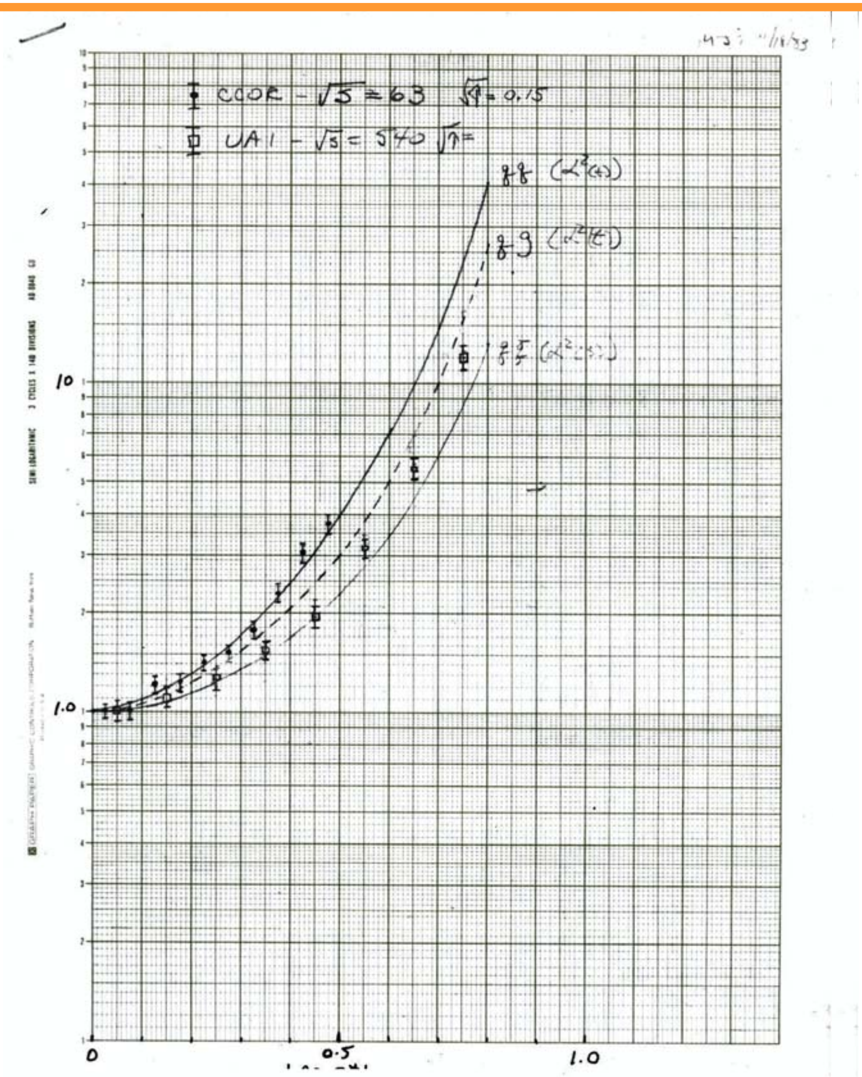


Figure 10 (*a*) Distribution of cos θ^* for hard parton scattering as measured in the UA1 experiment (42). T normalization is defined by setting the value at cos $\theta^* = 0$ equal to 1. (*b*) Distribution of cos θ^* for ha parton scattering as measured in the UA2 experiment (43). All the different QCD processes (except for $\rightarrow q'\bar{q}'$), separately normalized to the data, lie in the area between the two dashed curves. The full line is t overall QCD prediction, normalized to the data.

see L. Di Lella ARNPS **35** (1985) 107--134

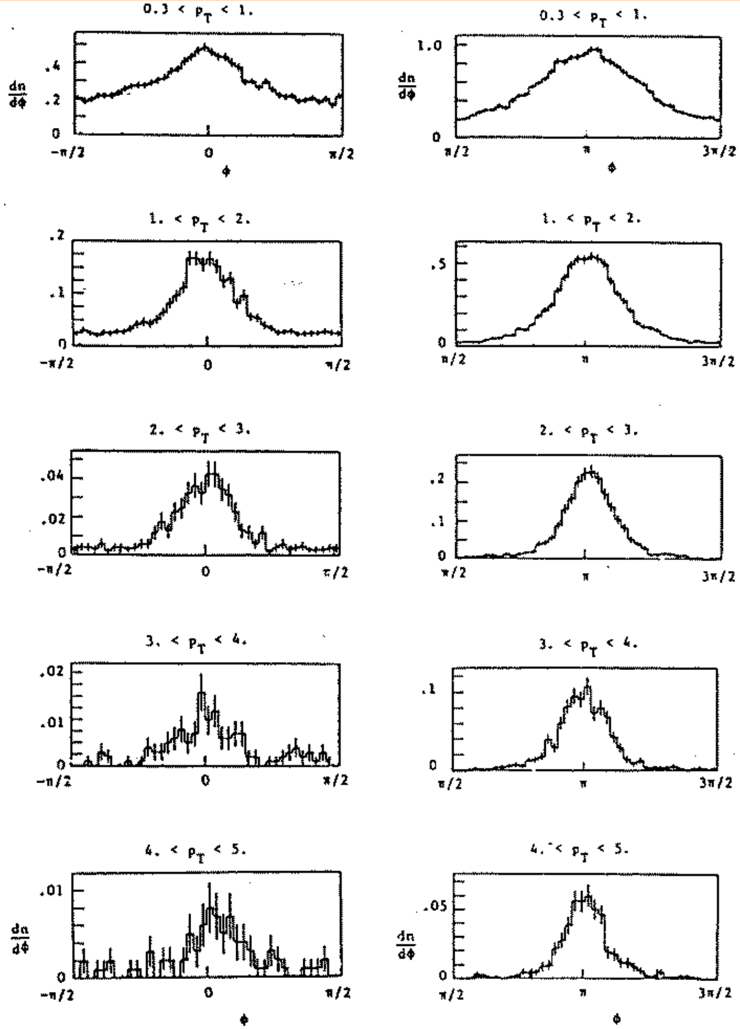
QCD really works: CCOR p-p follows q-q, UA1 p-$\bar{p}$ follows q-$\bar{q}$



plot I made in 1983

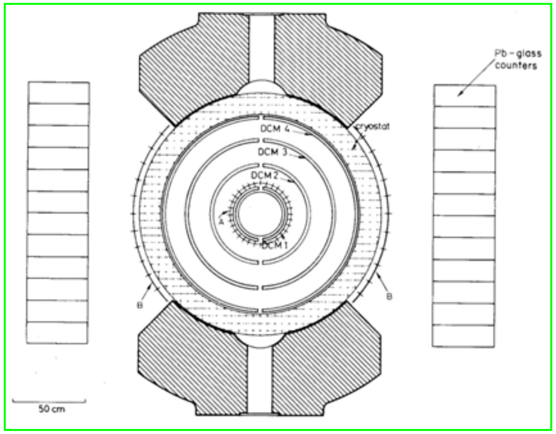
Why I believed in Jets: At the CERN ISR from 1975-1982 two-particle correlations showed unambiguously that high p_T particles come from jets

How everything you want to know about JETS was measured with 2-particle correlations



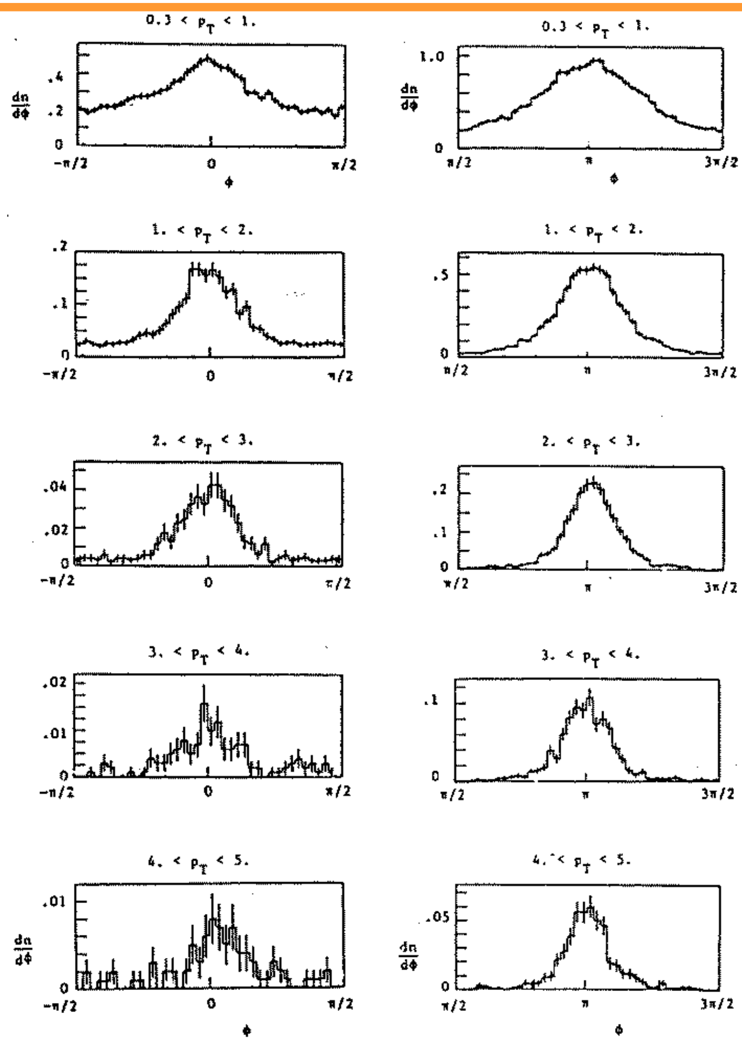
CCOR, A.L.S.Angelis, et al Phys.Lett. **97B**, 163 (1980)   PhysicaScripta **19**, 116 (1979)

$p_{Tt} > 7$ GeV/c vs p_T



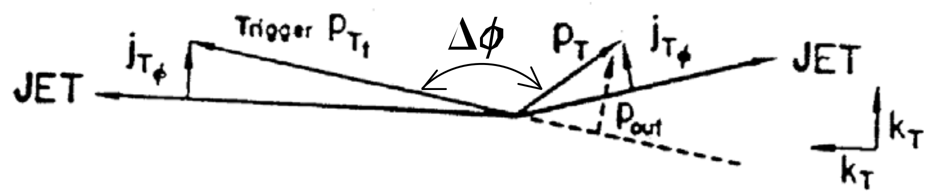
Away side $p_{out} \sim p_T \Delta\phi$ is not constant i.e $\Delta\phi \neq 1/p_T$, indicating jets not collinear in azimuth $\Rightarrow k_T$

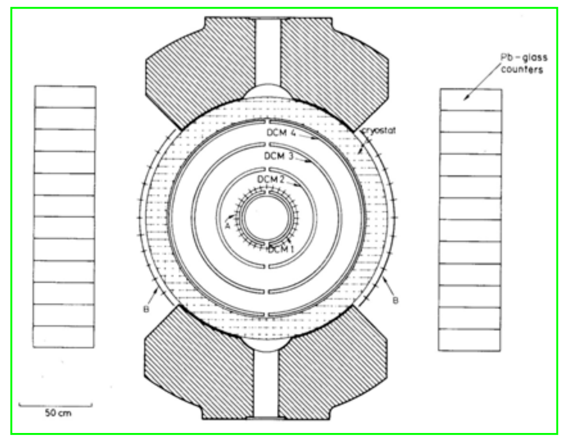
How everything you want to know about JETS was measured with 2-particle correlations



CCOR, A.L.S.Angelis, et al Phys.Lett. **97B**, 163 (1980) PhysicaScripta **19**, 116 (1979)

$p_{Tt} > 7$ GeV/c vs p_T





Away side p_{out}~$p_T\Delta\phi$ is not constant i.e $\Delta\phi \neq 1/p_T$, indicating jets not collinear in azimuth⇒ k_T

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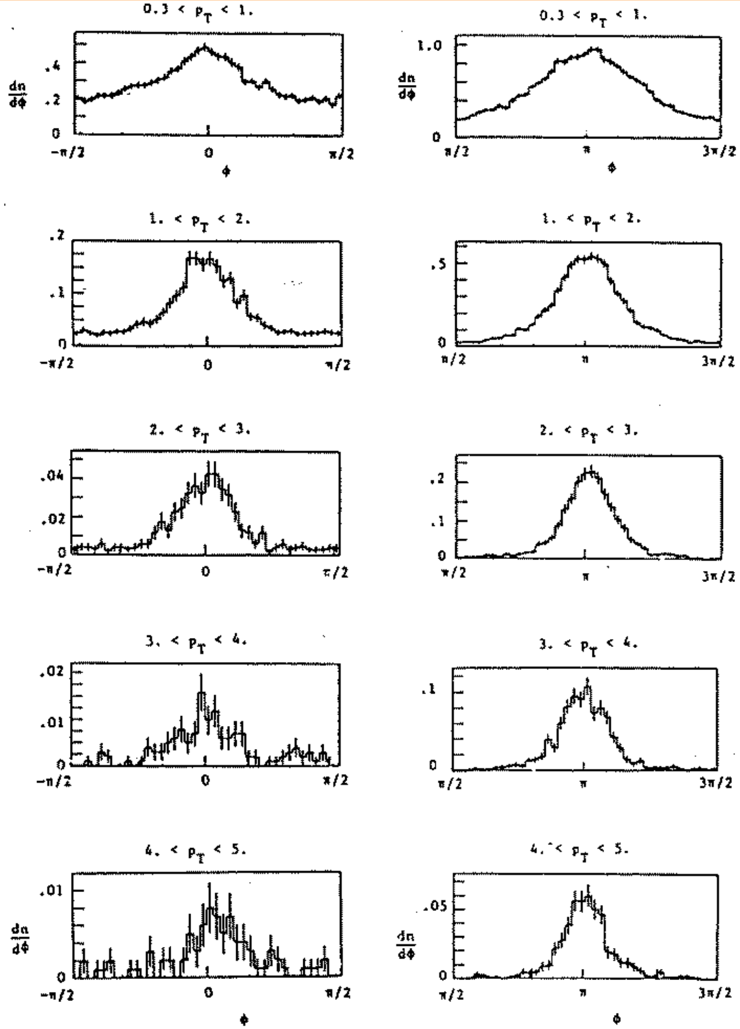

CCOR, A.L.S.Angelis, et al Phys.Lett. **97B**, 163 (1980) PhysicaScripta **19**, 116 (1979)

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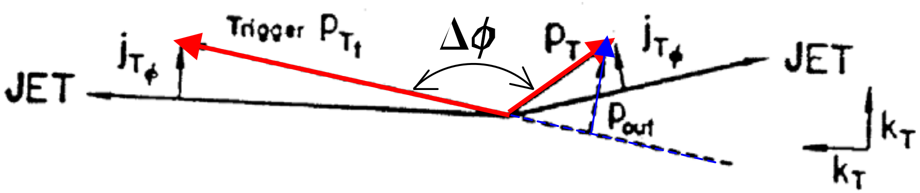
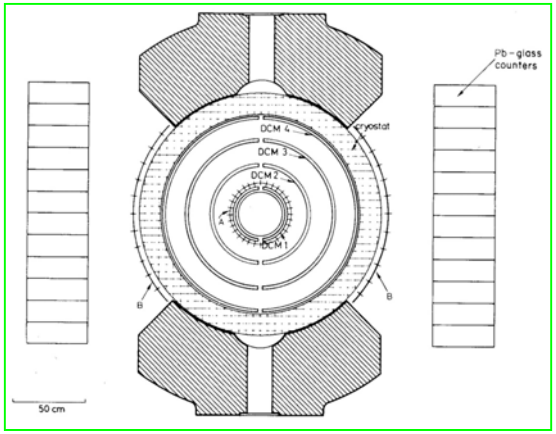
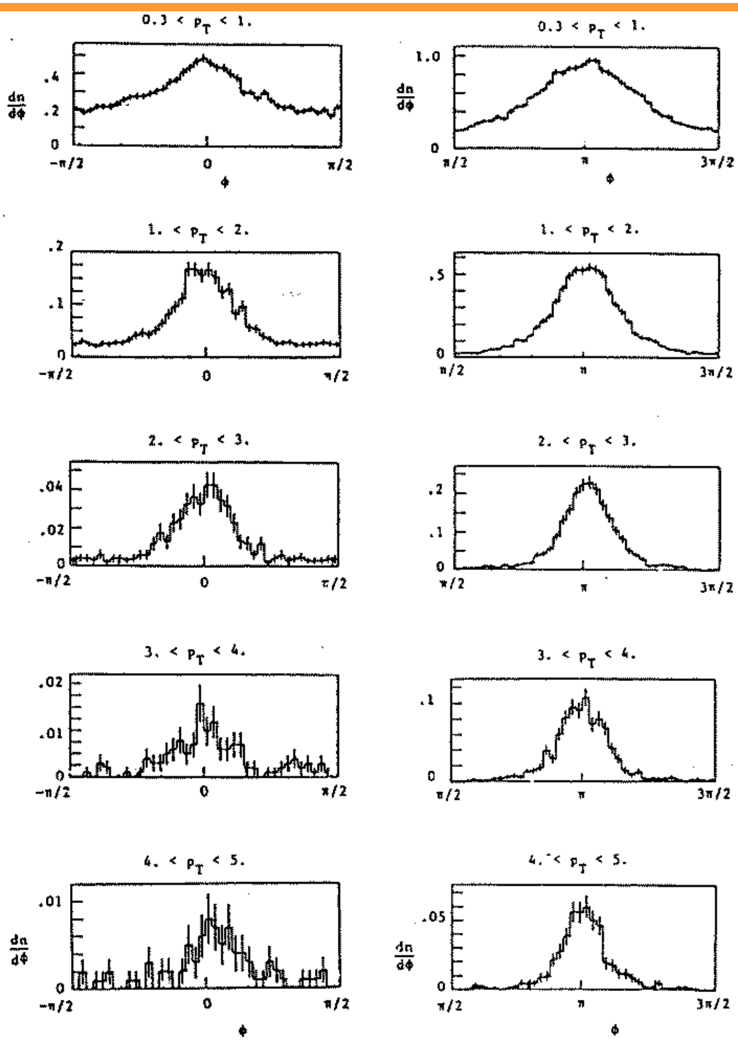




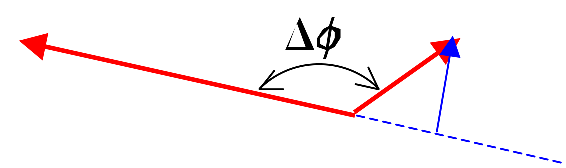
Away side $p_{out} \sim p_T \Delta\phi$ is not constant i.e $\Delta\phi \neq 1/p_T$, indicating jets not collinear in azimuth $\Rightarrow k_T$

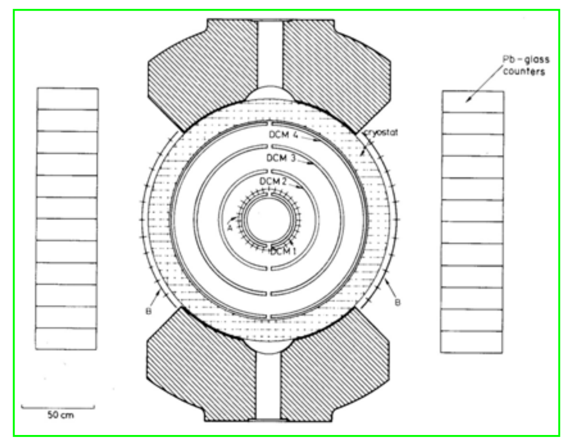
How everything you want to know about JETS was measured with 2-particle correlations



CCOR, A.L.S.Angelis, et al Phys.Lett. **97B**, 163 (1980) PhysicaScripta **19**, 116 (1979)

$p_{Tt} > 7$ GeV/c vs p_T





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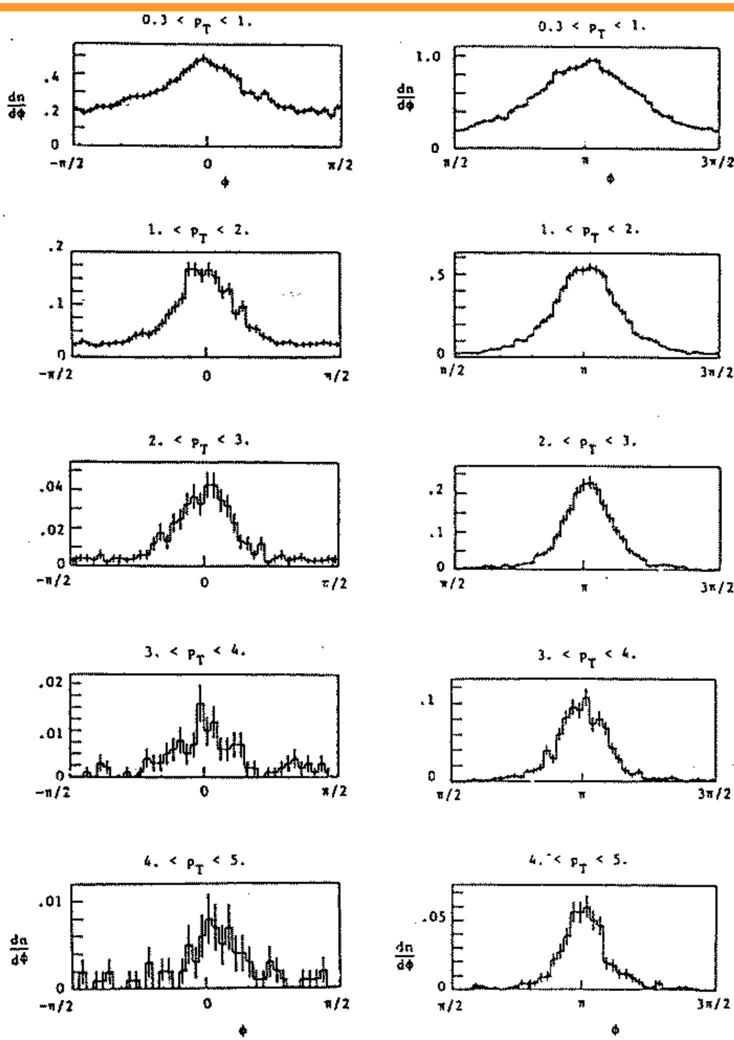
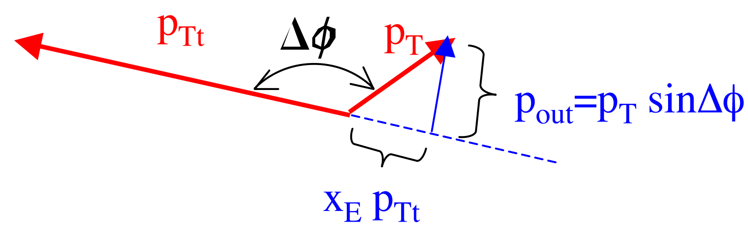
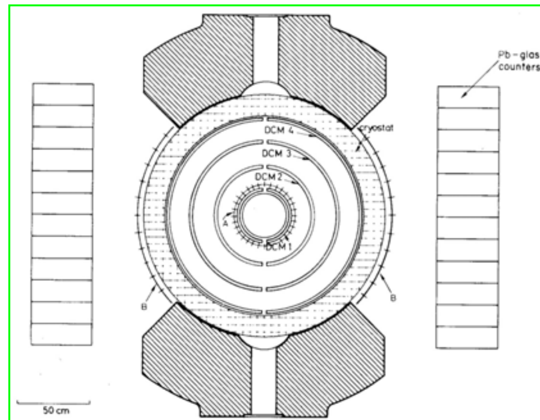
How everything you want to know about JETS was measured with 2-particle correlations



CCOR, A.L.S.Angelis, et al Phys.Lett. **97B**, 163 (1980)   PhysicaScripta **19**, 116 (1979)

$p_{Tt} > 7$ GeV/c vs p_T





Away side $p_{out} \sim p_T \Delta\phi$ is not constant i.e $\Delta\phi \neq 1/p_T$, indicating jets not collinear in azimuth $\Rightarrow k_T$

Feynman, Field and Fox said that x_E distribution from single particle or Jet measures D(z)

38 *R.P Feynman et al. / Large transverse momenta*

FFF Nucl.Phys. **B128**(1977) 1-65

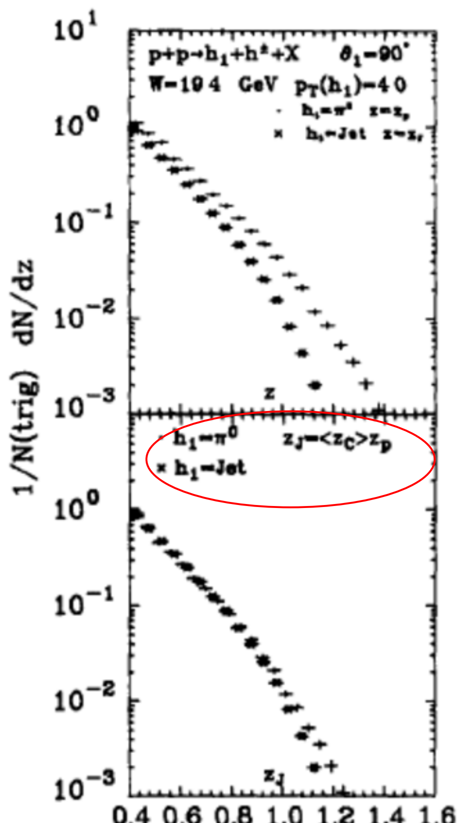


Fig. 23. Comparison of the π^0 and jet trigger away-side distribution of charged hadrons in pp collisions at $W = 19.4$ GeV, $\theta_1 = 90°$, and $p_\perp$ (trigger) = 4.0 GeV/c from the quark-quark scattering model. The upper figure shows the single-particle (π^0) trigger results plotted *versus* $z_p = -p_x(h^\pm)/p_\perp(\pi^0)$ and the jet trigger plotted *versus* $z_J = -p_x(h^\pm)/p_\perp(\text{jet})$ (see table 1). In the lower figure, we plot *both versus* z_J, where for the jet trigger $z_J = z_J$ but for the single-particle trigger $z_J = \langle z_c \rangle z_p$. The away hadrons are integrated over all rapidity Y and $|180° - \phi| \leqslant 45°$ and the theory is calculated using $\langle k_\perp \rangle_{h\to q} = 500$ MeV. • $h_1 = \pi^0$, × h_1 = jet.

"There is a simple relationship between experiments done with single-particle triggers and those performed with jet triggers. The only difference in the opposite side correlation is due to the fact that the 'quark', from which a single-particle trigger came, always has a higher $p_\perp$ than the trigger (by factor $1/z_{trig}$). The away-side correlations for a single-particle trigger at $p_\perp$ should be roughly the same as the away side correlations for a jet trigger at $p_\perp$ (jet)= $p_\perp$ (single particle)/ $<z_{trig}>$".

As shown at the ISR by Darriulat, etc, and believed by most High Energy Physicists

P. Darriulat, et al, Nucl.Phys. **B107** (1976) 429-456

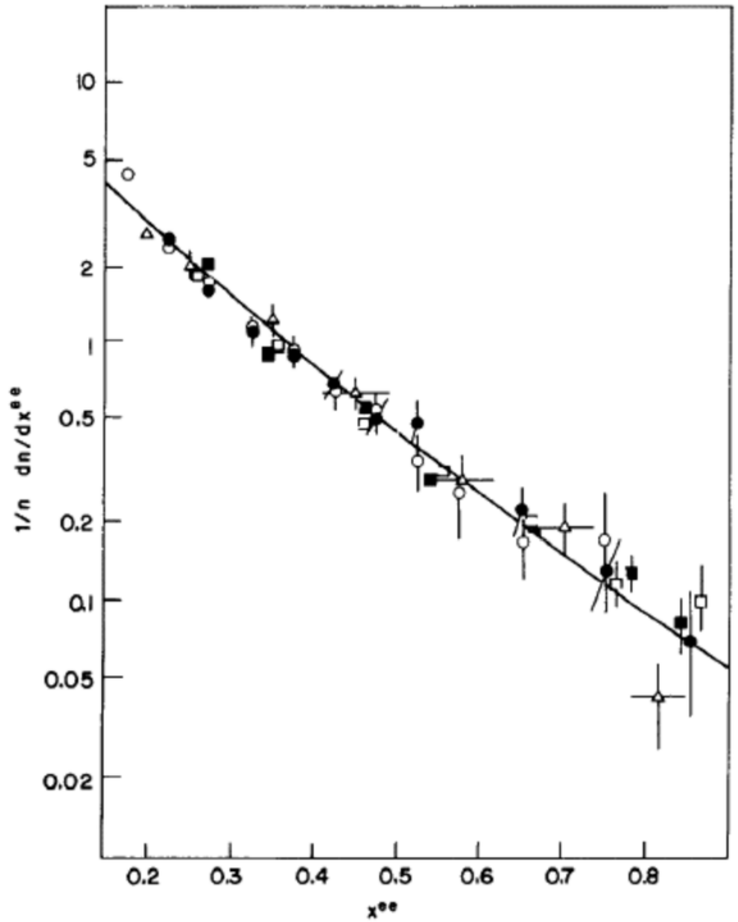


Figure 21 Jet fragmentation functions measured in different processes: ν-p interactions (*open triangles*, Van der Welde 1979); e^+e^- annihilations (*solid line*, Hanson et al 1975); and pp collisions (*full circles* CS, $p_T < 6$ GeV/c, *open circles* CS, $p_T > 6$ GeV/c, *full squares* CCOR, $p_T > 5$ GeV/c, *open squares* CCOR, $p_T > 7$ GeV/c).

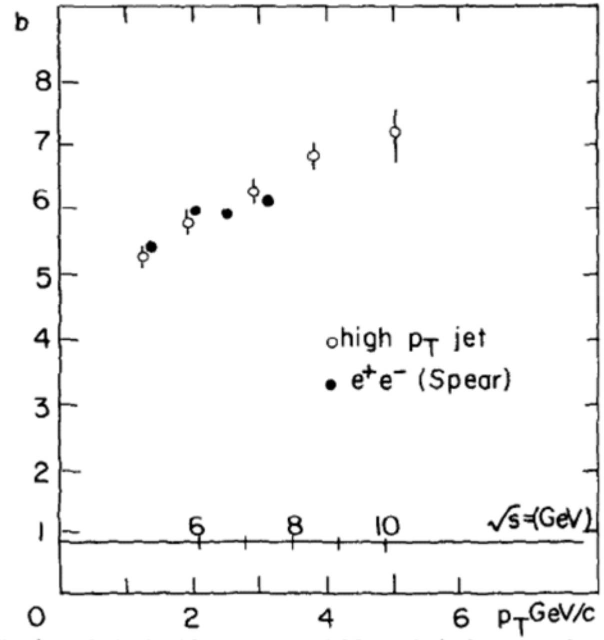
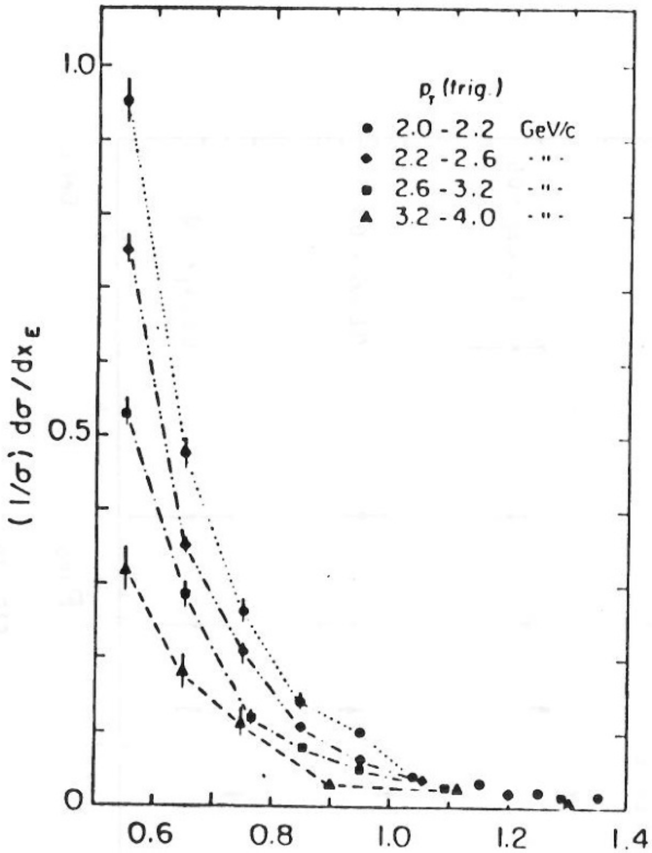


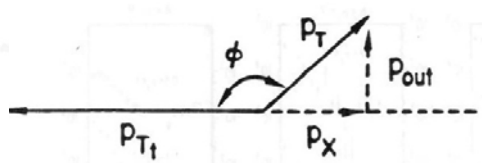
Figure 19 The slopes *b* obtained from exponential fits to the jet fragmentation function in the interval $0.2 < z < 0.8$ in e^+e^- annihilation (*full circles*) and LPTH data of the BS Collaboration (*open circles*).

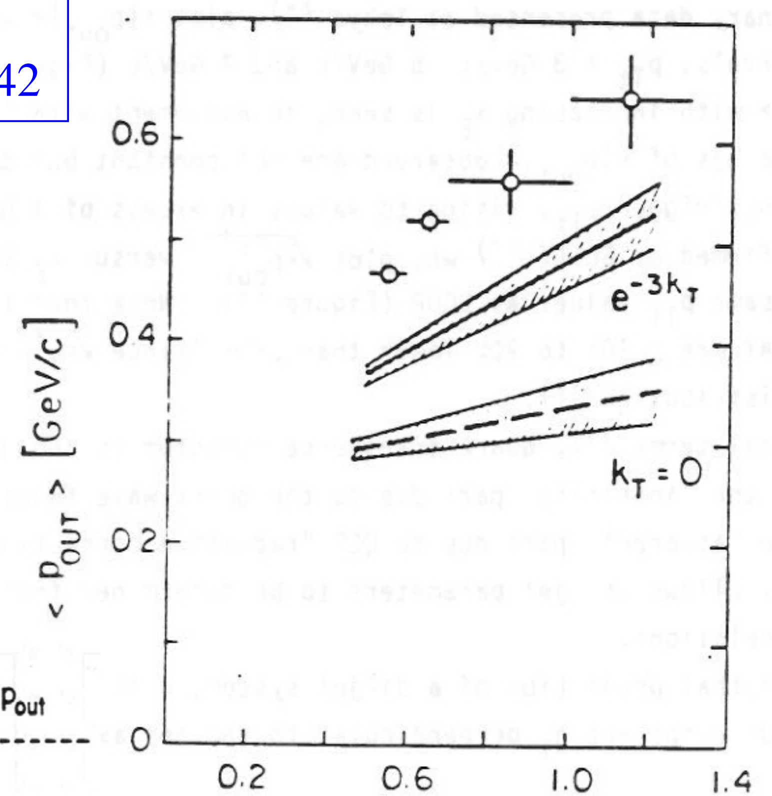
Figures from P. Darriulat, ARNPS **30** (1980) 159-210 showing that Jet fragmentation functions in νp, e^+e^- and pp (CCOR) are the same with the same dependence of *b* (exponential slope) on "$\hat{s}$"

But first, CCHK discovered k_T by lack of x_E scaling



CCHK
NP**B127**(1977) 1-42

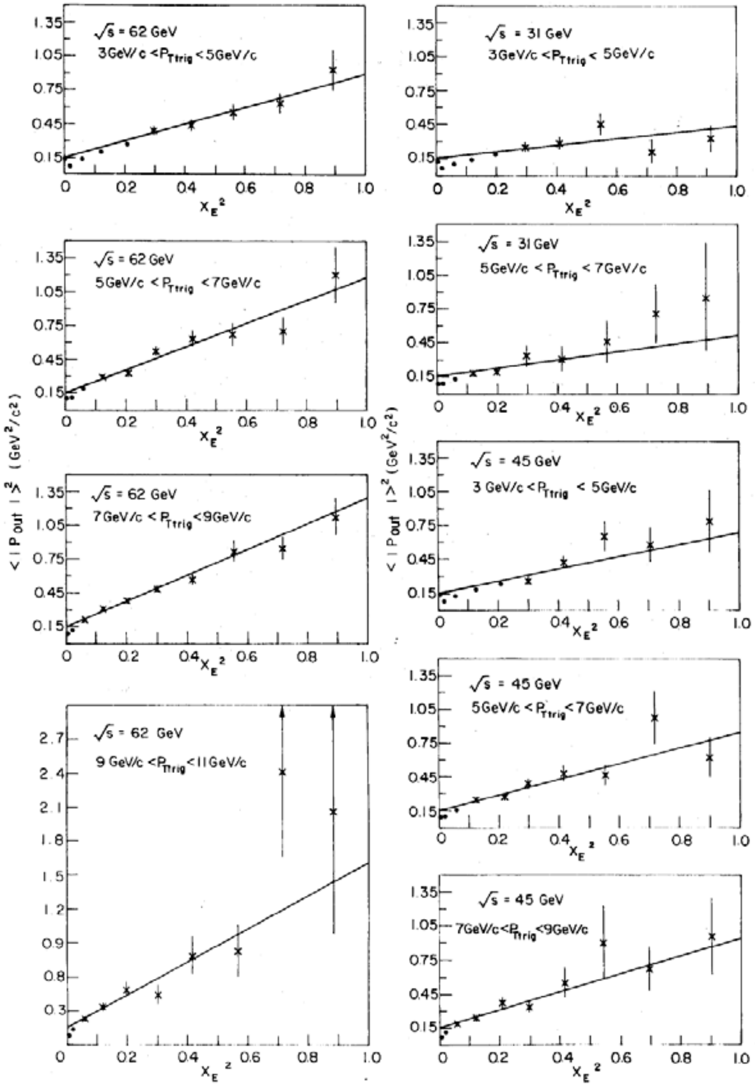


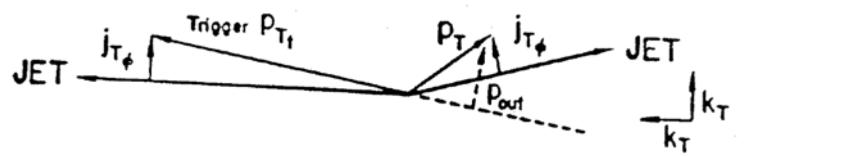


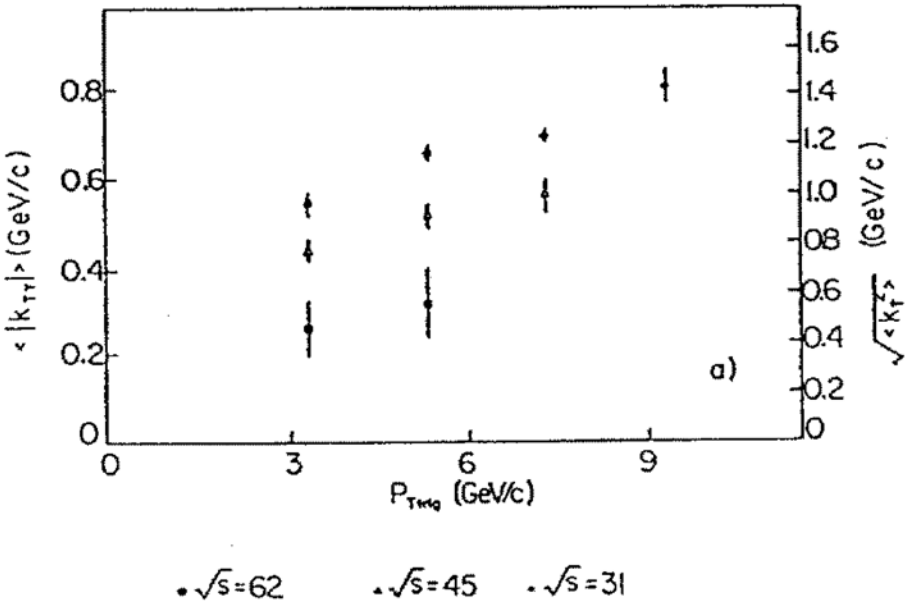
Cern-College de France, Heidelberg, Karlsruhe (CCHK) collab. found that x_E distributions were not universal for $2<p_{Tt}<4$ GeV/c and attributed this to the large out of plane momentum p_{out} which was not constant with x_E as in fragmentation but increased with increasing x_E as if the di-jets were not collinear due to initial state k_T

CCOR $\langle|p_{out}|\rangle^2$ vs x^2_E --k_T not constant

$$\langle|p_{out}|\rangle^2 = x_E^2[2\langle|k_{Ty}|\rangle^2 + \langle|j_{Ty}|\rangle^2] + \langle|j_{Ty}|\rangle^2$$





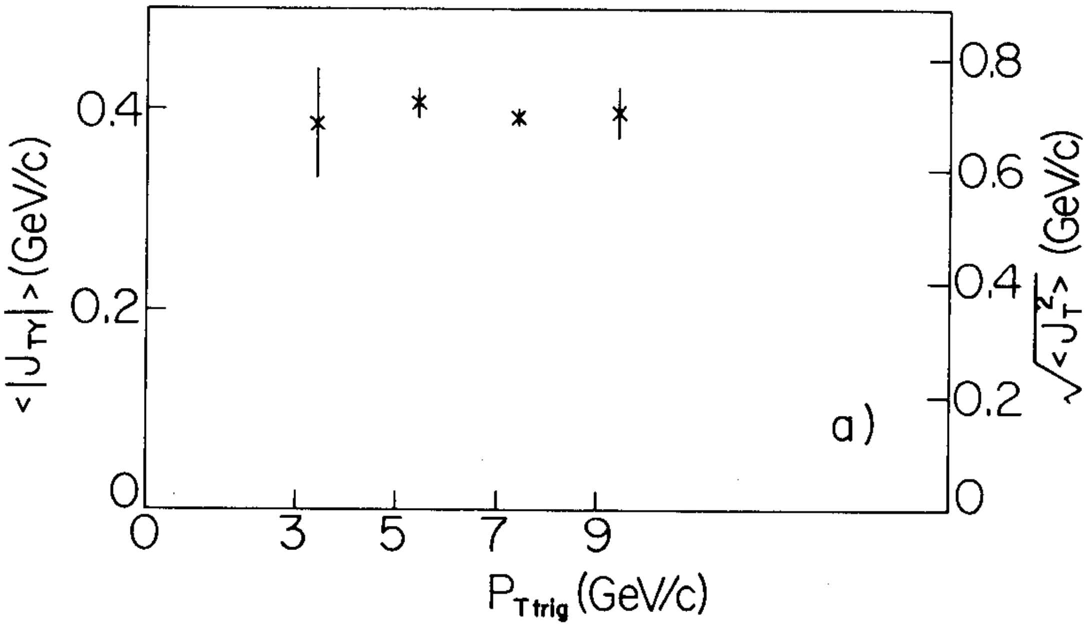


CCOR PLB 97 (1980) 163

k_T varies with p_{Tt} and $\sqrt{s}$

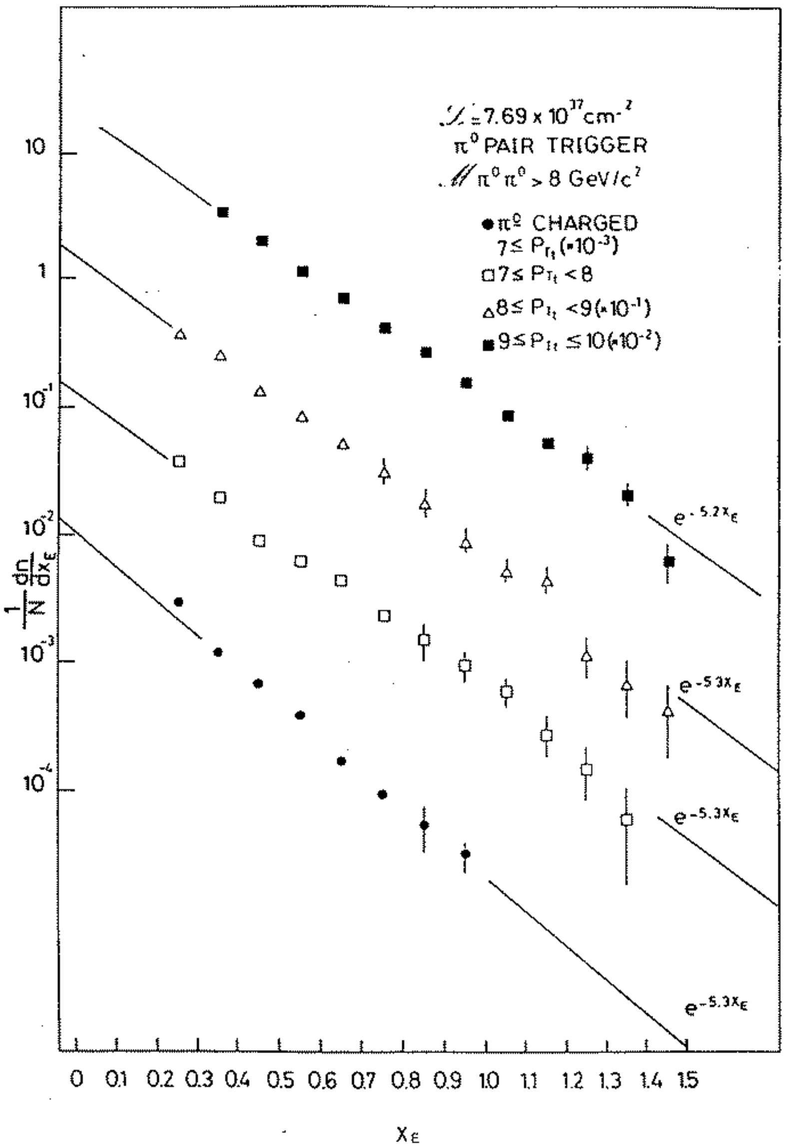
Not intrinsic !

But j_T is constant-independent of p_{Tt} and √s Characteristic of jet fragmentation



- it took the $e^+ e^-$ people several more years to get this correct---because they didn't understand the seagull effect: ($j_T < p_T$)

x_E distribution measures fragmentation fn.



CCOR, Physica Scripta **19**, 116 (1979)

$$x_E \sim z/\langle z_{trig}\rangle$$

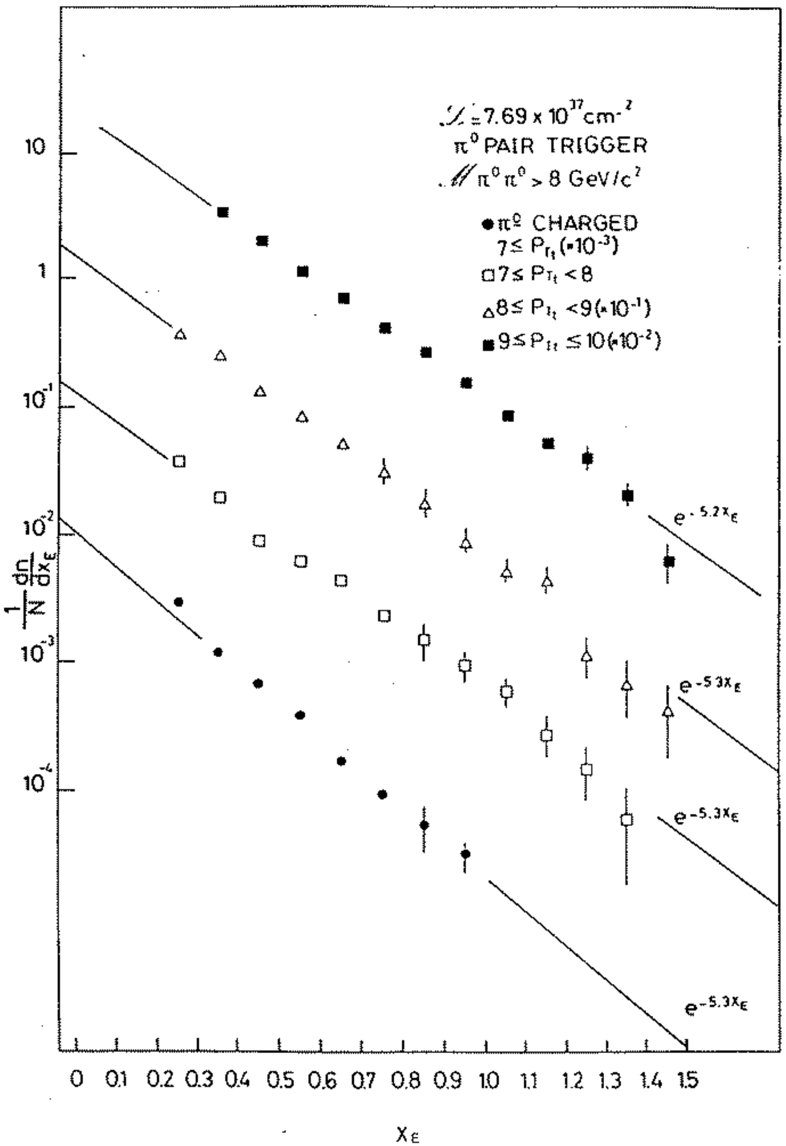
$\langle z_{trig}\rangle$=0.85 measured

$$e^{-5.3xE} \Rightarrow D^q_\pi(z) \sim e^{-6z}$$

- independent of p_{Tt}

See M. Jacob's talk Proc. EPS 1979 Geneva (CERN). p512

x_E distribution measures fragmentation fn. not!



CCOR, Physica Scripta **19**, 116 (1979)

$$x_E \sim z/\langle z_{trig}\rangle$$

$\langle z_{trig}\rangle$=0.85 measured

$$e^{-5.3xE} \Rightarrow D^q_\pi(z) \sim e^{-6z} \;*$$

- independent of p_{Tt}

See M. Jacob's talk Proc. EPS 1979 Geneva (CERN). p512

* but we did learn something new on this issue in PHENIX.

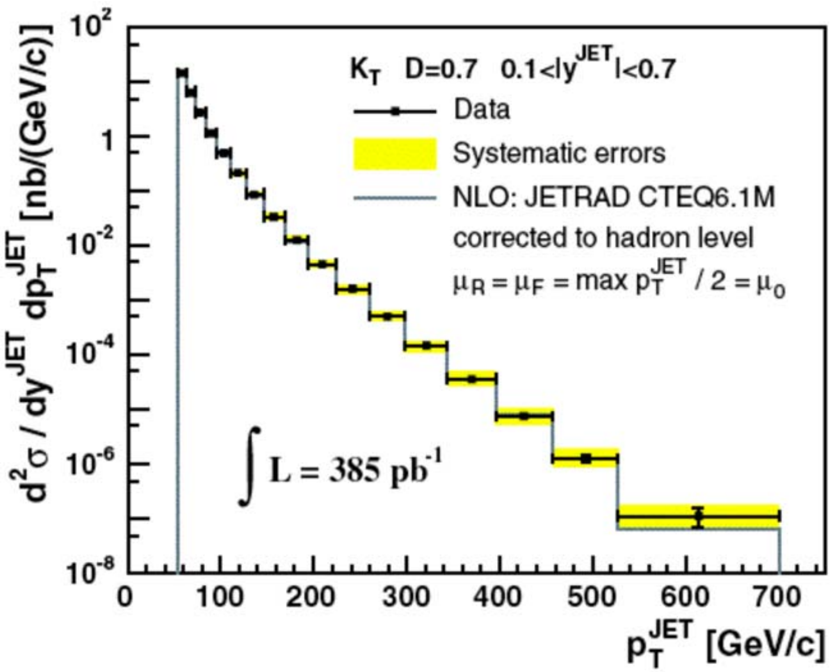
This is the only thing we didn't understand correctly at the ISR. Maybe we could be forgiven because Feynman said it.

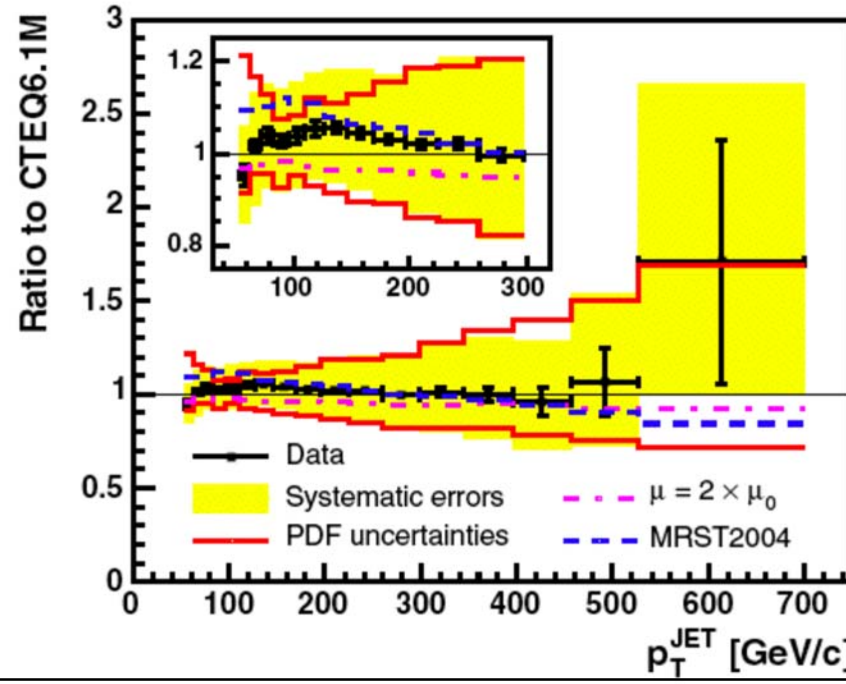
* At RHIC we learned that the x_E distribution from a trigger fragment does not measure the fragmentation function.

For more info, see: M. J. Tannenbaum "Review of hard scattering and jet analysis", PoS (CFRNC2006) cited by Kronfeld and Quigg in "Resource Letter: QCD" arXiv:1002.5032v2. Even better, see J. Rak and M. J. Tannenbaum, "High p_T physics in the Heavy Ion Era", Cambridge University Press, available May 2013 http://www.cambridge.org/us/knowledge/isbn/item6947421/High-/?site_locale=en_US

For the past decade these single and two-particle techniques were used exclusively at RHIC for hard-scattering, with outstanding results...

Jet measurements of QCD in pp collisions are now standard after a ~30 year learning curve





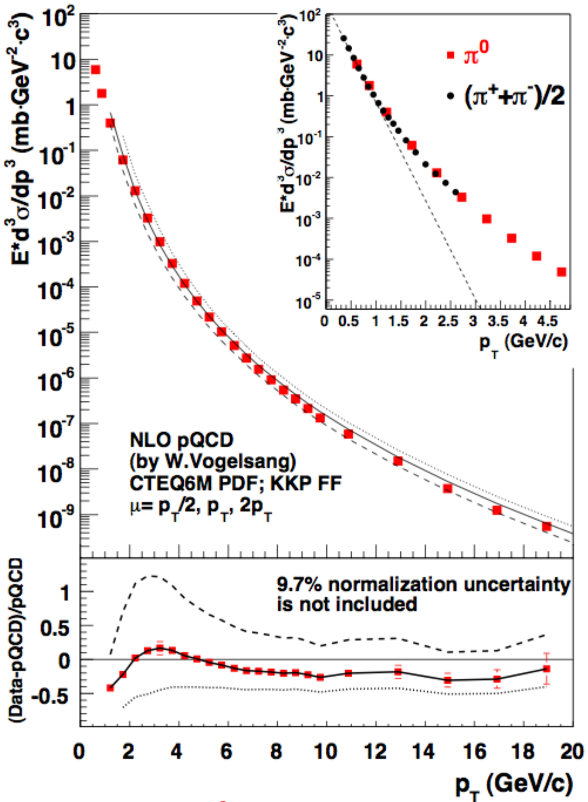
The measured crosssection is in agreement with NLO pQCD predictions after the necessary nonperturbative parton-to-hadron corrections are taken into account. i.e. Make sure to read the fine print!

A. Abulencia, et al, CDF PRL 96 (2006) 122001-k_T algorithm

At RHIC, inclusive single particles provide a precision pQCD probe, well calibrated in pp, dAu… collisions

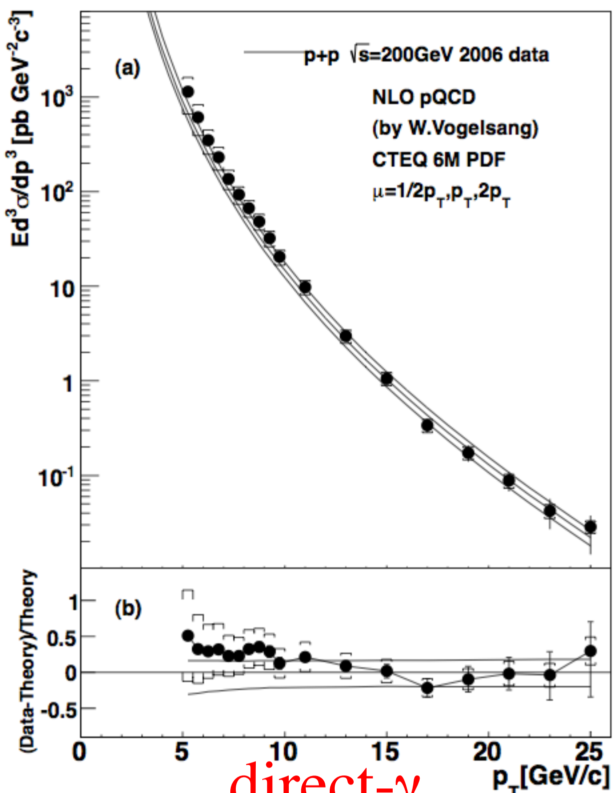
PHENIX excellent in hard-scattering measurements via single-inclusive and two-particle correlations, STAR better with Jets

PHENIX PRL**91** (2003) 241803



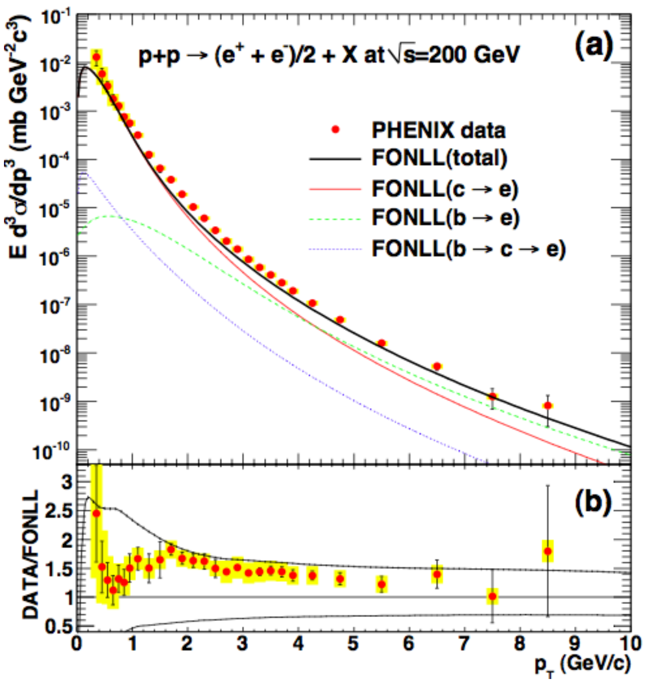
π^0

PHENIX arXiv:1205.5533



direct-γ

PHENIX PRL**97** (2006) 252002

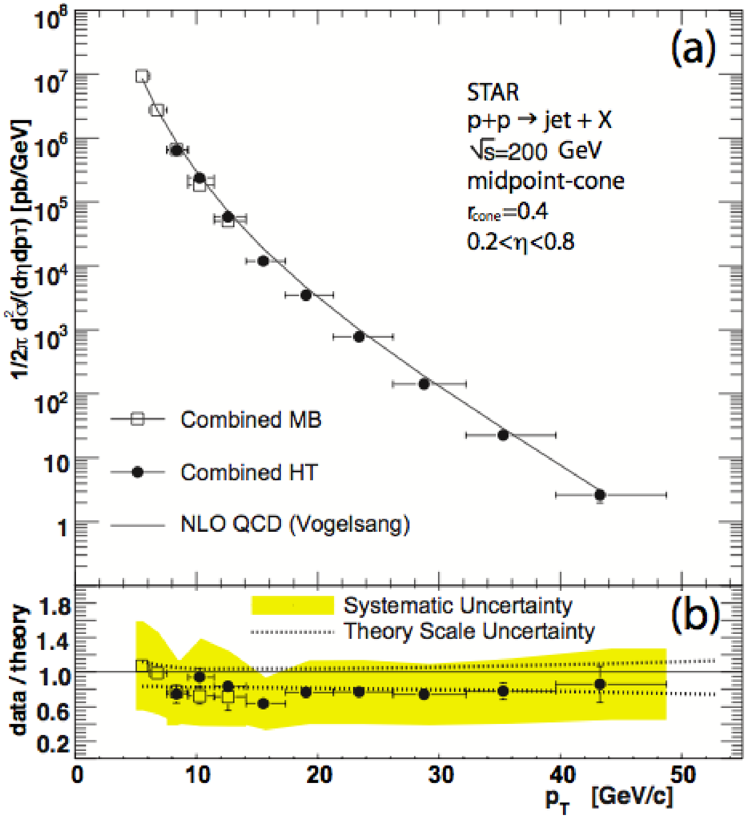


direct-single-e from c and b quark decays

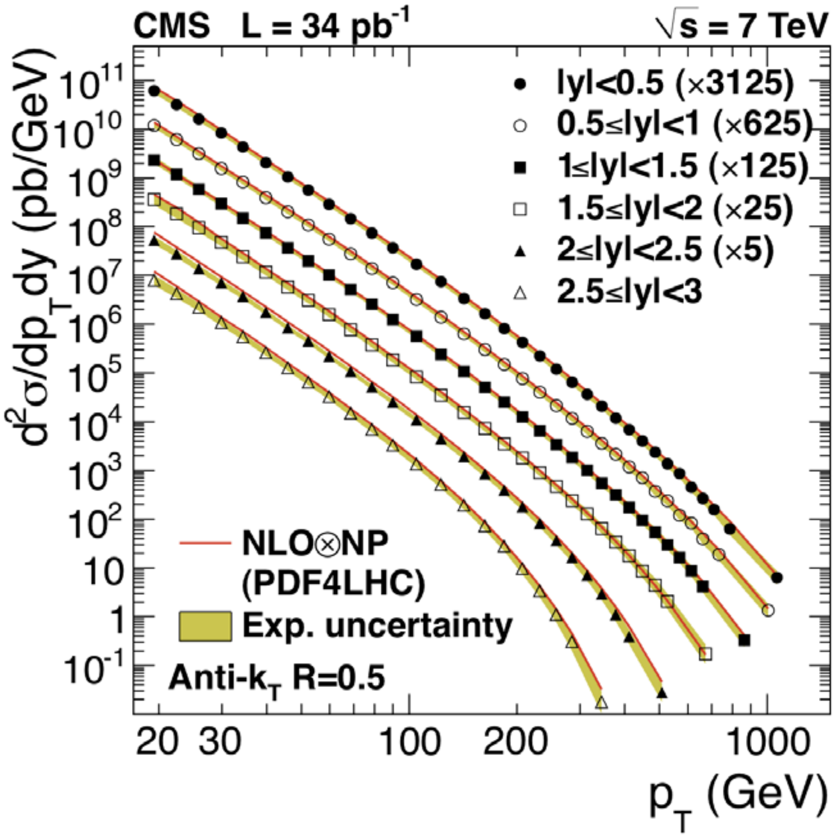
In p-p collisions, since 1978, NLO pQCD agrees very well with all measurements.

Of course LHC MUCH Better with Jets

STAR PRL**97** (2006) 252001



CMS PRL**107** (2011) 132001



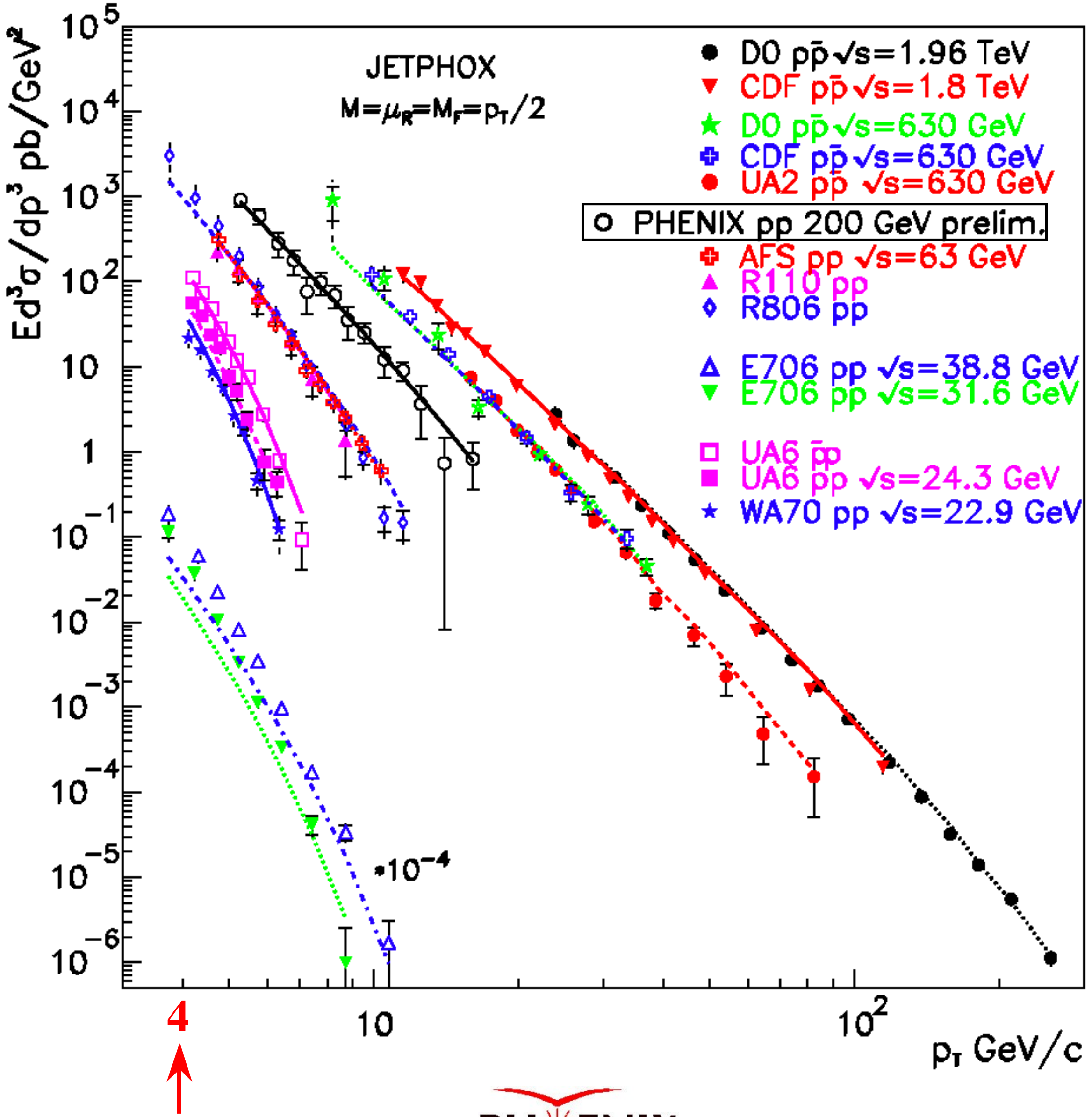
Again agree very well with NLO pQCD in p-p collisions. But, I have known that QCD worked for hard scattering since 1978. What I learn from the CMS plot is that partons are pointlike up to $Q^2 \approx t \approx 2p_T^{\,2} = 2{,}000{,}000$ GeV^2 i.e. r<<1.4 x 10^{-4} fm!!

Direct γ p-p data and pQCD c. 2007

PHENIX direct-γ in p-p
PRL **98** (2007) 012002

PHENIX direct photon p-p data clarify longstanding data/theory puzzle

P. Aurenche et al Phys. Rev. D **73**, 094007 (2006)



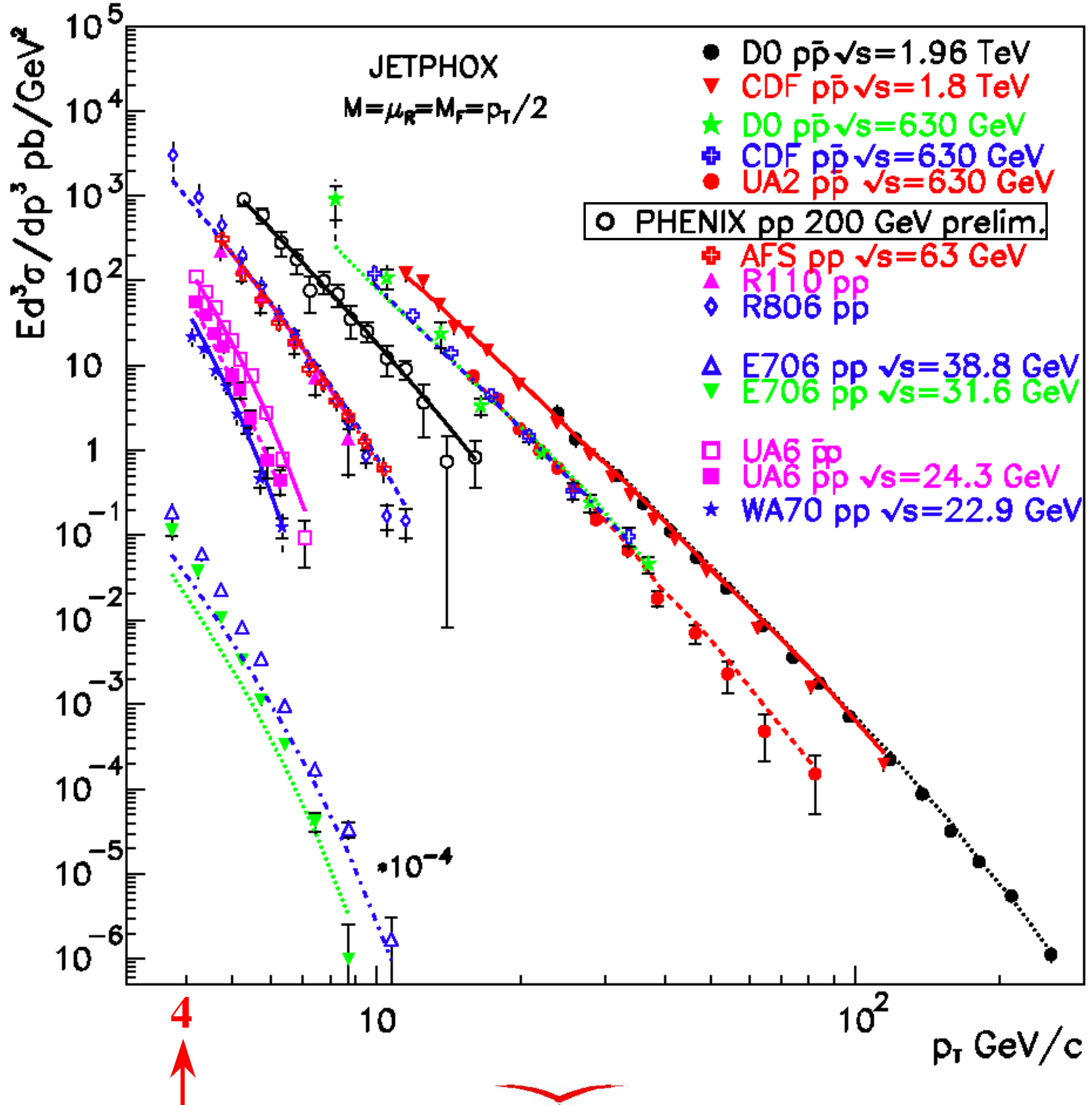
Direct γ p-p data and pQCD c. 2007

PHENIX direct-γ in p-p
PRL **98** (2007) 012002

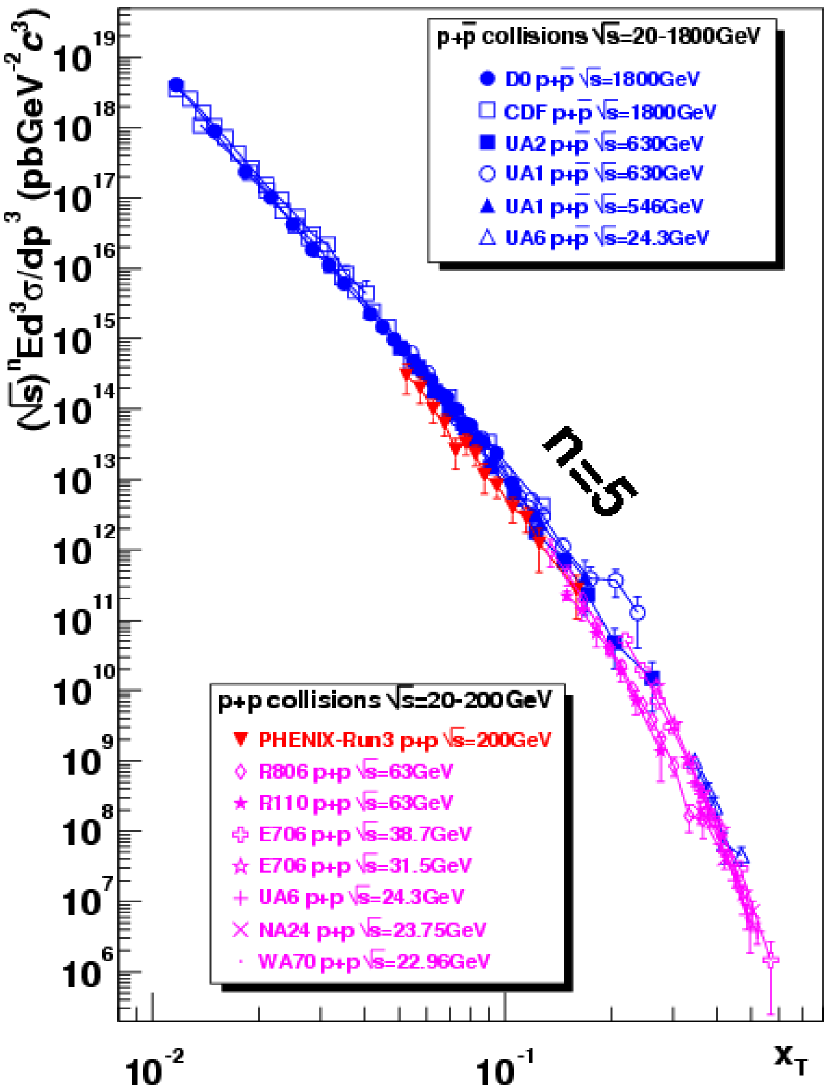
PHENIX direct photon p-p data clarify longstanding data/theory puzzle

P. Aurenche et al Phys. Rev. D **73**, 094007 (2006)

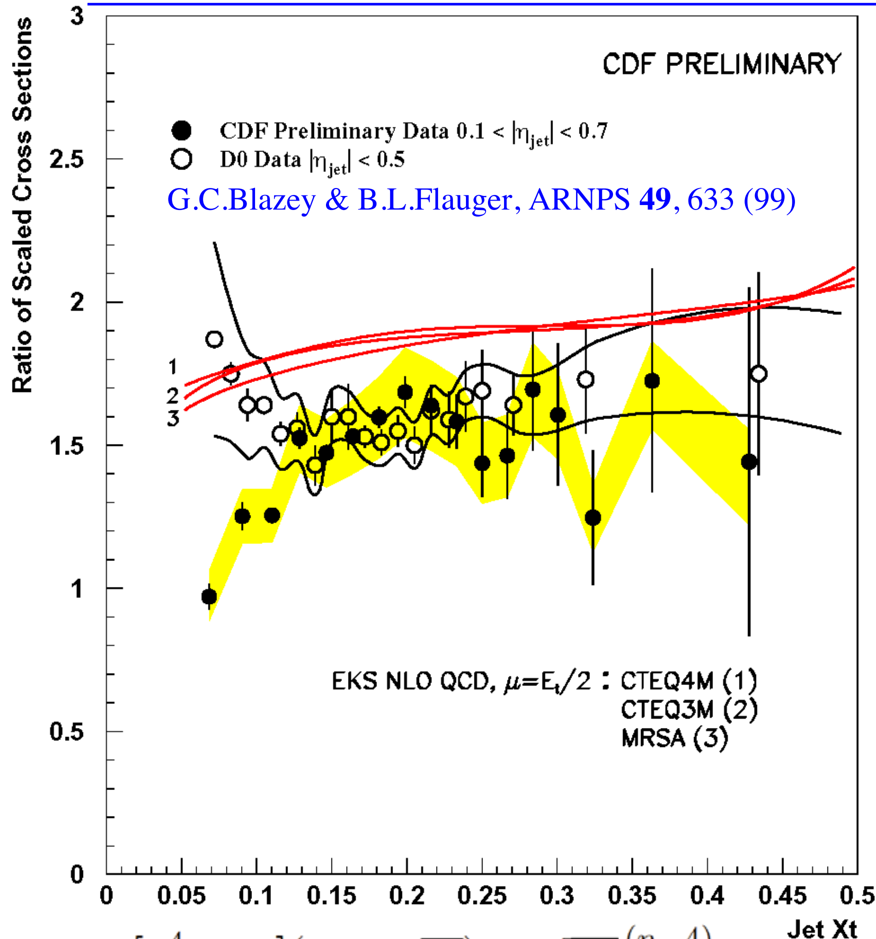
New PHENIX p-p results this year arXiv:1205.5533 are even better!



x_T scaling: a) Direct-γ b) Jets



Jets-Ratio of Scaled Cross Sections 630/1800

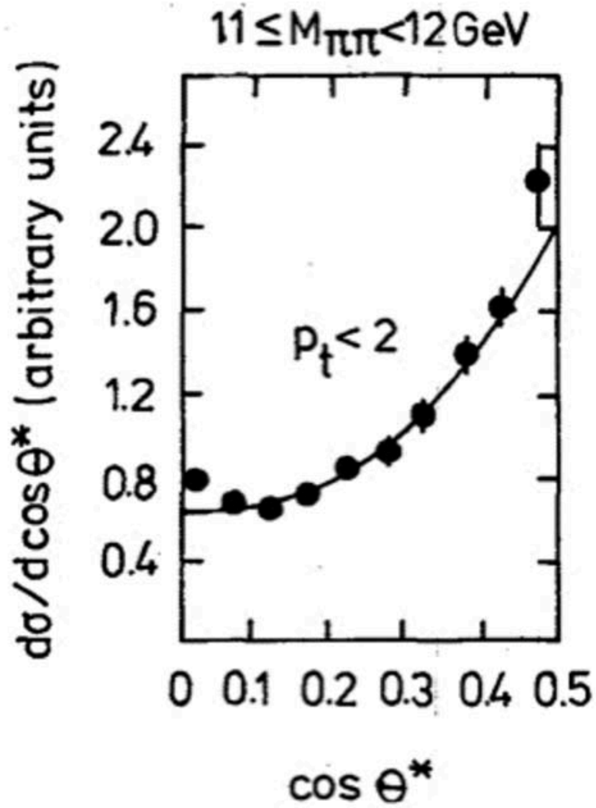


$$\frac{[p_T^4\,\sigma_{\rm inv}](x_T,\sqrt{s_1})}{[p_T^4\,\sigma_{\rm inv}](x_T,\sqrt{s_2})} = \sqrt{\frac{s_2}{s_1}}^{\,(n-4)}$$

Direct γ n≈5 2005

Jets n≈4.5

The END



Gunther Wolf, Rapporteur, Proc. 1982 ICHEP

Recap of discoveries and techniques from the CERN ISR in 1972-1982

G. Giacomelli and M. Jacob, Phys. Rept. **55** (1979) 1-132
M. Jacob and K. Johnsen, CERN Yellow Report 84-13

- The rapidity plateau. (Not discussed in this talk.)
- Hard scattering in p-p collisions via particle production at large p_T which proved that the partons of DIS strongly interacted with each other. x_T scaling measurements to find the underlying physics.
- direct lepton ($e^{\pm}$) production from the decay of (unknown at that time-1974) particles composed of b and c quarks.
- first and only J/Psi cross section measurement for all pair $p_T \geq 0$ at a hadron collider, until PHENIX at RHIC [PRL **92** (2004) 051802] and CDF [PRD **71**(2005) 032001 (15 years after their first publication)]
- direct photon production
- Proof using same-side and away side two particle correlations that high p_T particles in p-p collisions are produced from states with two roughly back-to-back jets which are the result of scattering of constituents of the nucleons as described by QCD, which was developed during the course of these measurements.

Conclusions from ISR

- Hard Scattering in p-p collisions was discovered at the CERN ISR in 1972 by the method of leading particles.
- A very large flux of high p_T pions was observed with a power-law tail which varied systematically with $\sqrt{s}$, the c.m. energy of the collision.
- The huge flux of high p_T particles proved that the partons of DIS strongly interacted with each other.
- Scaling arguments allowed the form of the force law between 'partons' to be determined but there was some early confusion caused by initial transverse momentum k_T which distorted the spectra.
- Further ISR measurements utilizing inclusive single or pairs of hadrons established that high transverse momentum particles are produced from states with two roughly back-to-back jets which are the result of scattering of constituents of the nucleons as described by Quantum Chromodynamics.